Government Polytechnic, Sonepur

LECTURE NOTE

SUBJECT NAME- MECHANICAL METALLURGY

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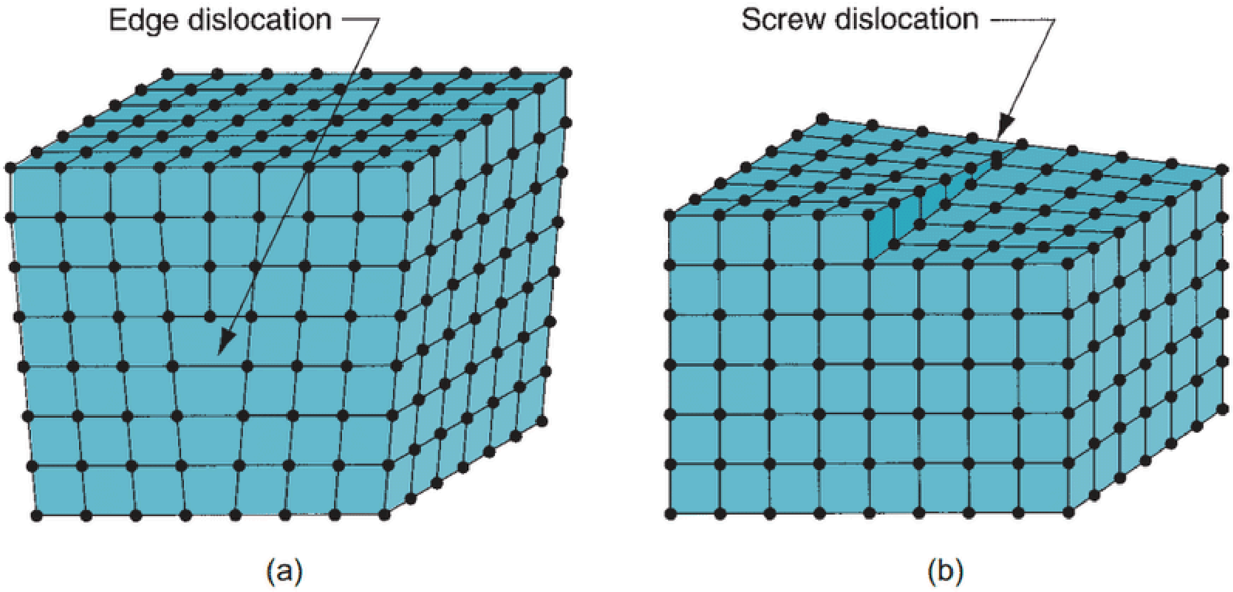
1. Introduction

Line Defects - Dislocations

Line defects are one-dimensional (1D) defects in a crystal lattice where the atomic arrangement is disturbed along a line. The most important type of line defect is the **dislocation**, which plays a critical role in the mechanical behavior of materials, especially in plastic deformation.

Types of Dislocations



1. Edge Dislocation

- An extra half-plane of atoms is inserted into the crystal lattice.
- The **Burgers vector** (b) is perpendicular to the dislocation line.
- Movement occurs through **glide (slip)** in response to shear stress.
- At high temperatures, movement can also occur via **climb**, which involves diffusion of atoms or vacancies.

2. Screw Dislocation

- Formed when a shear stress distorts the crystal structure, creating a helical twist.
- The Burgers vector is **parallel** to the dislocation line.
- Movement occurs in a helical (spiral-like) manner.

Movement of Dislocations

- **Slip (Glide):** Movement along the slip plane under shear stress, causing permanent deformation.
- **Climb:** Movement perpendicular to the slip plane due to atomic diffusion, occurring at high temperatures.
- **Cross-Slip:** A screw dislocation moves from one slip plane to another.

Effects of Dislocations on Materials

- **Plastic Deformation:** Dislocations allow metals to deform plastically under stress.
- **Work Hardening:** Increased dislocation density strengthens the material.
- **Creep:** At high temperatures, dislocations contribute to slow deformation.
- **Fracture and Fatigue:** Dislocations influence crack initiation and propagation.

Edge dislocation climb is a diffusion-controlled process that allows an edge dislocation to move **perpendicular** to its slip plane. Unlike glide, which occurs due to shear stress, climb involves atomic diffusion and occurs at **high temperatures** where atomic mobility is significant.

Sources of Dislocations

Dislocations are line defects in a crystal lattice where the atoms are out of position, and they play a crucial role in plastic deformation. The sources of dislocations are essential for understanding how these defects are generated and multiplied within materials.

Key Sources of Dislocations

- **Frank-Read Sources**:
  - These are mechanisms by which dislocations are generated and multiplied. A Frank-Read source involves a dislocation segment pinned at both ends. When a shear stress is applied, the segment bows out, eventually forming a dislocation loop that can expand and create new dislocations
- **Grain Boundaries**:
  - Irregularities at grain boundaries can produce dislocations that propagate into the grain. Steps and ledges at grain boundaries are important sources of dislocations, especially during the early stages of plastic deformation
- **Homogeneous Nucleation**:

  - This involves the spontaneous formation of dislocations within the crystal lattice due to the rupture of atomic bonds along a line. It is less common compared to other mechanisms but can occur under high stress conditions
- **Plastic Deformation**:
  - The density of dislocations increases significantly during plastic deformation. Existing dislocations can spawn new ones, contributing to the overall dislocation density

Dislocation in various crystals

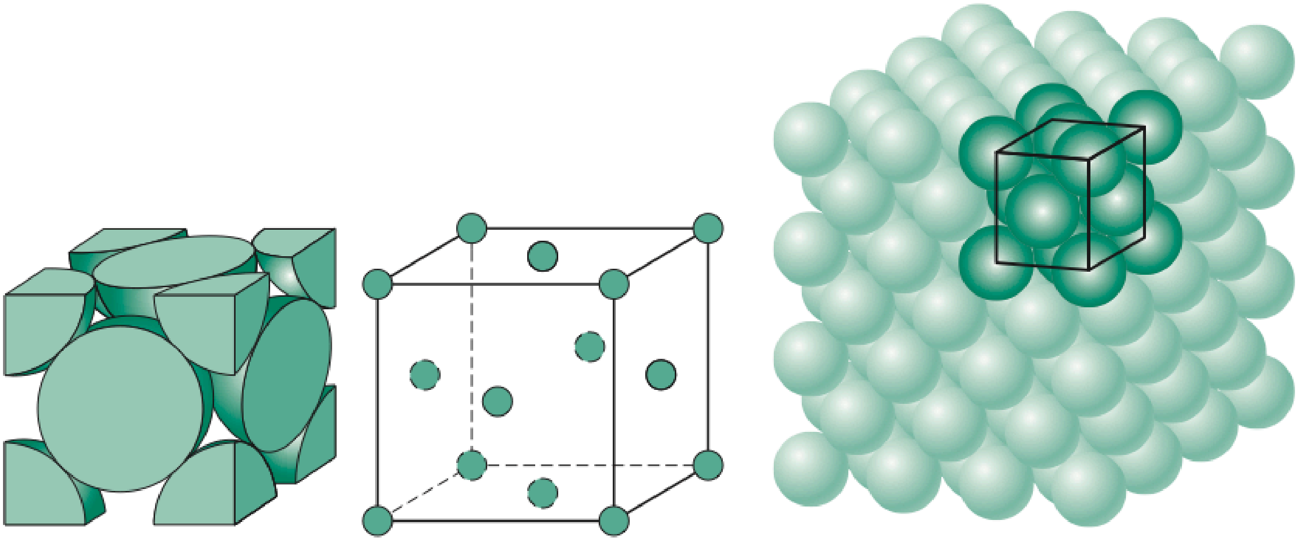
Dislocations are line defects in a crystal structure that play a crucial role in the mechanical properties of materials. They enable plastic deformation and influence hardness, ductility, and strength. The nature and behavior of dislocations vary depending on the crystal structure.

Types of Dislocations

- **Edge Dislocation** – A missing or extra half-plane of atoms inserted into the crystal lattice.
- **Screw Dislocation** – A helical distortion of the lattice caused by shear stress.
- **Mixed Dislocation** – A combination of edge and screw dislocations.

Dislocations in Different Crystal Structures

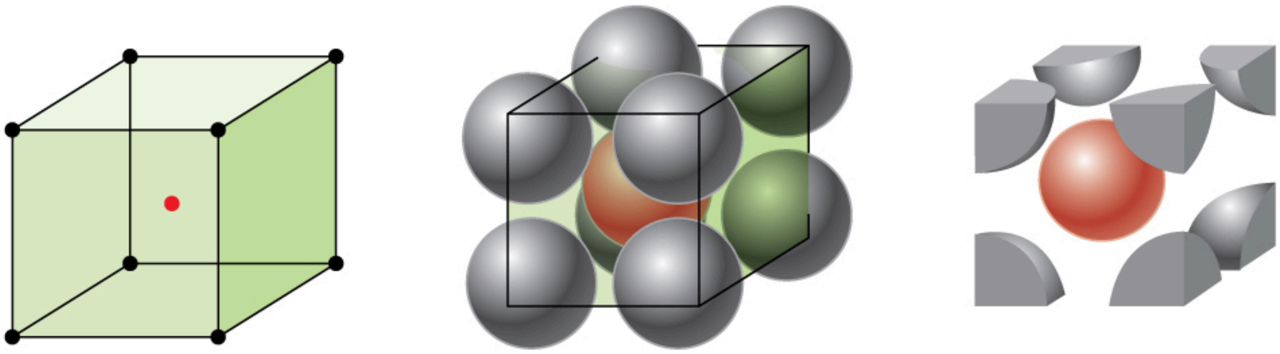
Face-Centered Cubic (FCC) Crystals



- **Examples**: Aluminum (Al), Copper (Cu), Gold (Au), Silver (Ag), Nickel (Ni)
- **Dislocation Behavior**:

  - High number of slip systems (12) → High ductility
  - Lower Peierls stress (low resistance to dislocation motion) → Easy slip
  - Mostly **Shockley partial dislocations** and **stacking faults**
  - Twinning is less common compared to HCP structures

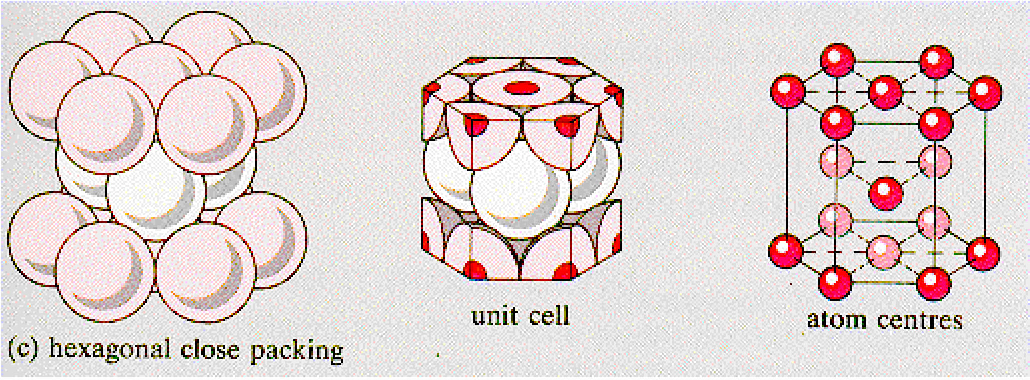
Body-Centered Cubic (BCC) Crystals



Body-centered cubic structure

- **Examples**: Iron (Fe), Tungsten (W), Chromium (Cr), Molybdenum (Mo)
- **Dislocation Behavior**:
  - Fewer slip systems compared to FCC, but still significant (48 possible slip systems, though not all active at once)
  - Higher Peierls stress → More difficult dislocation motion
  - Brittle at low temperatures, but ductile at higher temperatures
  - Non-planar core structure of dislocations → Dislocation motion is harder

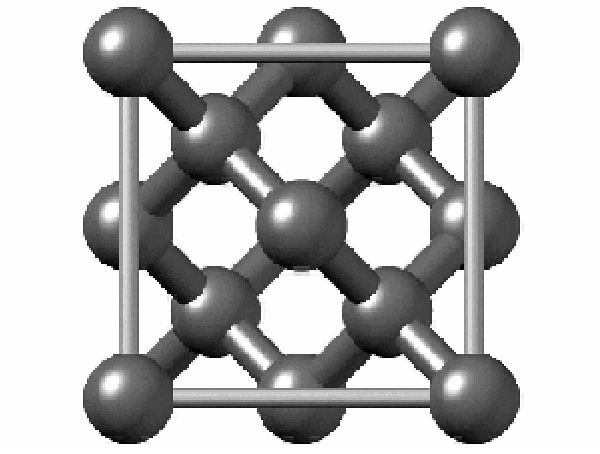
Hexagonal Close-Packed (HCP) Crystals



- **Examples**: Magnesium (Mg), Titanium (Ti), Zinc (Zn), Cobalt (Co)
- **Dislocation Behavior**:
  - Fewer slip systems (depends on c/a ratio) → Lower ductility
  - High anisotropy in mechanical properties

  - Twinning is a major deformation mechanism along with slip
  - Prismatic and basal slip systems dominate
  - In the hexagonal close-packed metals, the only plane with high atomic density is the basal plane (0001). The axes (1120) are the close-packed directions.
  - Since there is only one basal plane per unit cell and three (1120) directions, the hcp structure possesses three slip systems. The limited number of slip systems is the reason for the extreme orientation dependence and low ductility in hcp crystals.

Diamond Cubic (DC) Crystals



- **Examples**: Silicon (Si), Germanium (Ge), Diamond (C)
- **Dislocation Behavior**:
  - Extremely high Peierls stress → Very difficult dislocation motion
  - Dislocations move primarily by climb rather than glide
  - Brittle behavior due to low slip system availability

Ionic Crystals (e.g., NaCl, MgO, CaF_2)

- **Examples**: Sodium Chloride (NaCl), Magnesium Oxide (MgO), Calcium Fluoride (CaF_2)
- **Dislocation Behavior**:
  - Dislocations must maintain charge neutrality → Movement is restricted
  - Partial dislocations and stacking faults common
  - Slip occurs on specific planes (e.g., {110} in NaCl)
  - Usually brittle

Covalent Crystals (e.g., Si, GaAs, Diamond)

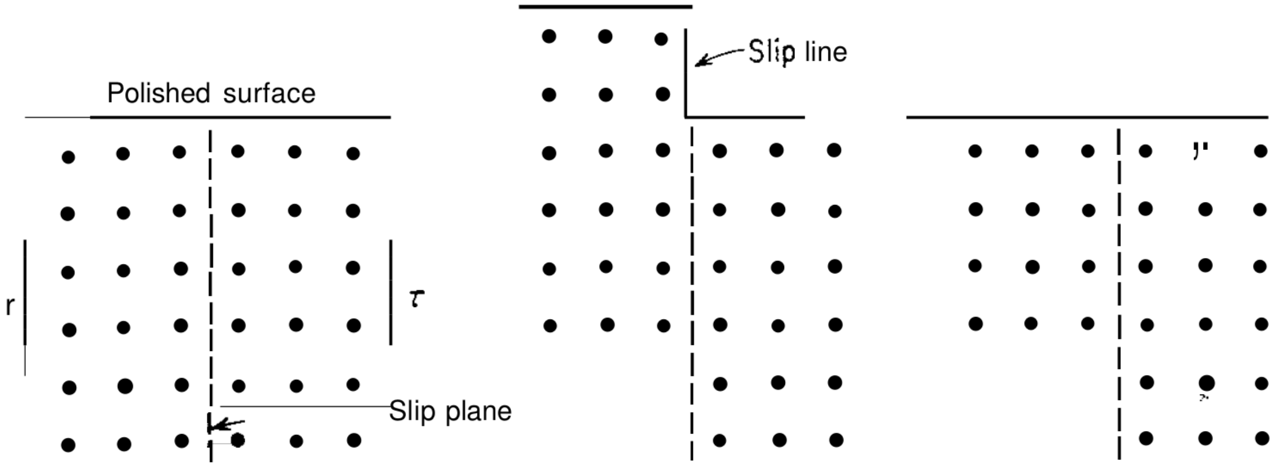
- **Examples**: Silicon (Si), Gallium Arsenide (GaAs), Diamond

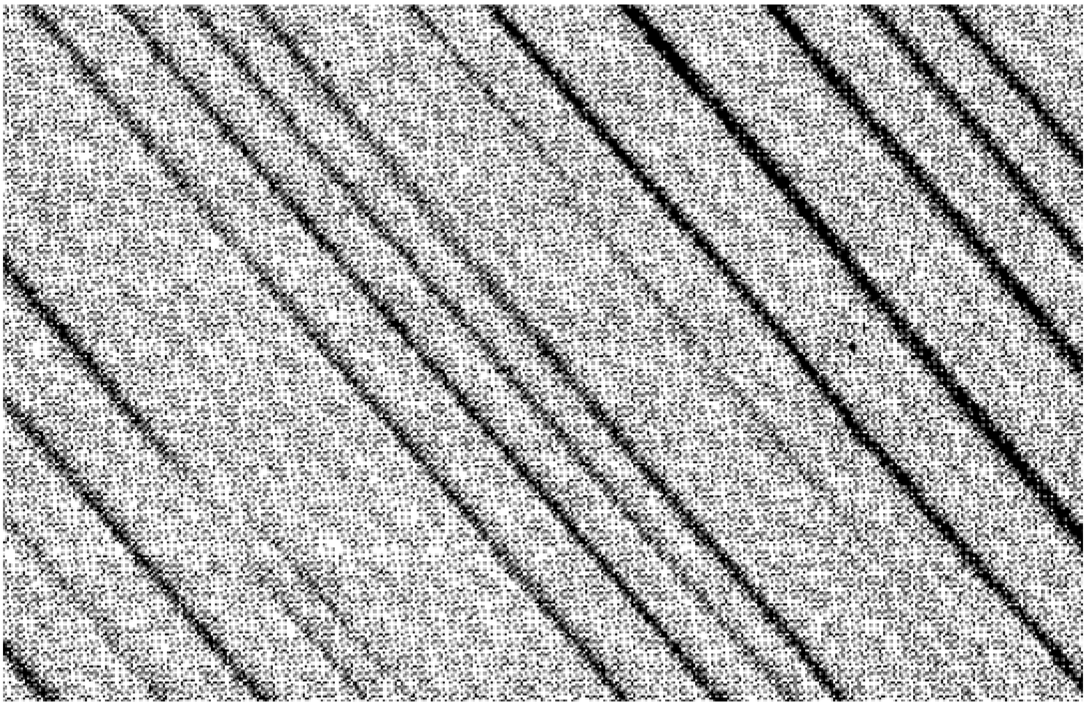
- **Dislocation Behavior**:
  - Strong directional bonding → Very high Peierls stress
  - Dislocations move slowly → Brittle behavior
  - Slip occurs on {111} planes but is difficult
  - Dislocation motion leads to defects affecting electronic properties (important in semiconductors)

Crystal Type	Examples	Slip Systems	Peierls Stress	Ductility
FCC	Cu, Al, Ni	Many (12)	Low	High
BCC	Fe, W, Mo	Moderate (not all active at once)	High	Moderate (brittle at low T)
HCP	Mg, Ti, Zn	Few (depends on c/a ratio)	Moderate	Low to moderate
Diamond Cubic	Si, Ge, C	Very few	Very high	Very brittle
Ionic	NaCl, MgO	Few, charge-neutrality restrictions	High	Brittle
Covalent	Si, GaAs	Few, strong bonds	Very high	Brittle

Deformation by Slip

The usual method of plastic deformation in metals is by the sliding of blocks of the crystal over one another along definite crystallographic planes, called **slip planes**.
Slip occurs when the shear stress exceeds a critical value. The atoms move an integral number of atomic distances along the slip plane, and a step is produced in the polished surface. When we view the polished surface from above with a microscope, the step shows up as a line, which we call a **slip line**.




[Straight slip lines in copper (500X)]

Generally the slip plane is **the plane of greatest atomic density** and the slip direction is the **closest-packed direction within the slip plane**.

The slip plane together with the slip direction establishes the slip system.

Slip System in Face-Centered Cubic (FCC) Structure

FCC Slip Plane

- The primary **slip planes** in an FCC crystal are the **{111} family of planes**.
- These are the most **densely packed planes**, meaning they have the **highest atomic packing density** and provide the easiest path for dislocation

movement.

FCC Slip Direction

- The **slip direction** is along the **⟨110⟩ family of directions**.
- These directions are the **shortest lattice vectors** in the FCC structure, making slip energetically favorable.

FCC Slip System

A slip system is defined as a combination of a **slip plane** and a **slip direction**.

For FCC, the slip system is:

{111}⟨110⟩

- **Slip Plane**: {111}
- **Slip Direction**: ⟨110⟩
- **Number of Slip Systems**: 12
  - There are **4 unique {111} slip planes**. (111), (1-11), (11-1), and (-111)
  - Each slip plane has **3 independent ⟨110⟩ directions**.
  - **Total slip systems: 4 × 3 = 12**

Why is FCC Highly Ductile?

- FCC metals (e.g., **Al, Cu, Ag, Ni, Au**) are highly **ductile** because they have **multiple active slip systems**.
- More slip systems allow the material to **deform easily** without fracturing.
- The ability to **accommodate plastic deformation in multiple directions** makes FCC metals excellent for applications requiring high formability (e.g., wires, sheets, and deep-drawing processes).

Slip System in Body-Centered Cubic (BCC) Structure

The **BCC crystal structure** is different from FCC in terms of slip behavior. Unlike FCC, which has **close-packed {111} planes**, BCC **does not** have a truly close-packed plane. Instead, slip occurs on **multiple planes**, making BCC metals generally **stronger but less ductile** than FCC metals.

BCC Slip Planes

BCC metals slip primarily on the following **planes**:

- **{110}** → Most favorable slip plane due to high atomic density.
- **{112}** → Secondary slip plane, activated under higher stresses.
- **{123}** → Less common, but can contribute to plastic deformation.

Since BCC metals **lack truly close-packed planes**, dislocations require more energy to move, meaning **BCC metals have higher strength but lower ductility** at low temperatures.

BCC Slip Directions

- The **slip direction** in BCC is **⟨111⟩**, because it represents the **shortest lattice vector** between atoms.
- **Why ⟨111⟩?**
  - The **⟨111⟩ direction** connects **nearest-neighbor atoms**, providing the most efficient pathway for dislocation motion.

BCC Slip Systems

A **slip system** is defined as a **slip plane** and a **slip direction**.

For BCC, the primary slip systems are:

Slip Plane {hkl}	Slip Direction ⟨uvw⟩	Number of Slip Systems
{110}	⟨111⟩	12
{112}	⟨111⟩	12
{123}	⟨111⟩	24
Total Slip Systems		**48**

- **{110} ⟨111⟩** is the most common slip system in BCC metals.
- At **low temperatures, BCC metals are stronger but less ductile** because dislocations require **thermal activation** to move.
- At **higher temperatures**, more slip systems become active, increasing ductility.

Crystal Structure	Slip Plane {hkl}	Slip Direction ⟨uvw⟩	Number of Slip Systems	Ductility
FCC (Face-Centered Cubic)	{111} (Octahedral)	⟨110⟩	12 (4 unique planes × 3 directions)	**High** (due to many slip systems)

Crystal Structure	Slip Plane {hkl}	Slip Direction ⟨uvw⟩	Number of Slip Systems	Ductility
BCC (Body-Centered Cubic)	{110}, {112}, {123}	⟨111⟩	48 (but fewer are active at low temperatures)	**Moderate to Low** (depends on temperature)
HCP (Hexagonal Close-Packed)	{0001} (Basal)	⟨1120̅⟩	3 (limited slip, highly anisotropic)	**Low** (depends on c/a ratio and temperature)
	{101̅0} (Prismatic)	⟨1120̅⟩	3	
	{101̅1} (Pyramidal)	⟨c + a⟩	6	

- **FCC metals** (e.g., aluminum, copper) are highly ductile due to **many active slip systems**.
- **BCC metals** (e.g., iron, tungsten) have multiple slip planes, but slip activation depends on **temperature**, making them **strong but less ductile** at low temperatures.
- **HCP metals** (e.g., magnesium, titanium) have **few active slip systems**, making them **brittle** unless additional slip or twinning occurs.

Slip in a Perfect Lattice – Expression for Critical Resolved Shear Stress (CRSS)

Slip in a **perfect lattice** occurs when a **shear stress** is applied along a crystallographic direction, causing atomic layers to slide over each other. This process is governed by the concept of **critical resolved shear stress (CRSS, denoted as τc\tau_c)**, which is the minimum shear stress required to initiate slip.

Schmid's Law for Slip

Schmid's Law gives the mathematical expression for the resolved shear stress (τ\tau) acting on a slip system:

$$\tau=\sigma\cos\varphi\cos\lambda$$

Where:

- τ = **Resolved shear stress** acting on the slip system
- σ = **Applied normal stress**

- φ = **Angle between the applied force direction and the slip direction**
- λ = **Angle between the applied force direction and the normal to the slip plane**

For slip to occur, the resolved shear stress must exceed the **critical resolved shear stress** (τc):

τ≥τc

τc is a **material property** and depends on factors like lattice structure, temperature, and strain rate.

Expression for Theoretical Shear Strength in a Perfect Lattice

In a perfect, defect-free lattice, the **theoretical shear strength** (τmax\tau_{max}) required to initiate slip can be estimated using a sinusoidal model of atomic interaction:

$$\tau = \tau_{max} \sin\left(\frac{2\pi x}{b}\right)$$

Where:

- τmax= **Maximum theoretical shear stress**
- x = **Displacement of atoms in the slip direction**
- b = **Interatomic spacing (Burgers vector magnitude)**

The maximum shear stress occurs when:

τmax≈G/10

Where **G** is the shear modulus of the material.

Why Real Metals Slip at Lower Stresses?

In **real metals**, slip occurs at much lower stresses than predicted by the theoretical shear strength. This happens due to the presence of **dislocations**, which reduce the required shear stress significantly.

The actual critical resolved shear stress in real metals is:

τc≈G/1000 to G/100

This is why metals can deform plastically at much lower stresses than a perfect crystal would predict.

Twinning & Deformation

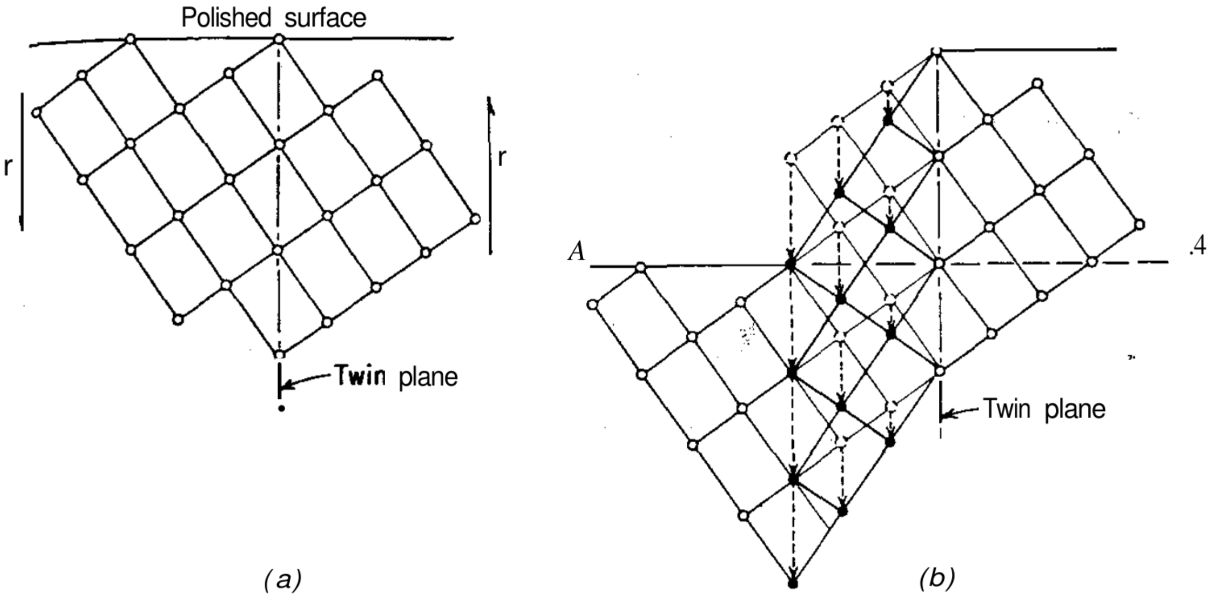
Another important plastic deformation mechanism which occurs in some metal is known as 'twinning'.

The shear forces produce atomic displacements such that the deformed lattice forms a mirror image of the undeformed lattice.

That is, the atoms on one side of the plane location is in mirror image position of the atoms on the other side.

The crystallographic plane of symmetry between the deformed and undeformed parts of the metal lattice is called the twinning plane.

Twinning is a major deformation notably seen in hexagonal close packed (HCP) metals like zinc and tin. Twinning also occurs in definite crystallographic planes and direction that depends on the crystal structure.



Types of Twins

- Mechanical twins
- Annealing twins.

Mechanical twins

Twins which are produced by mechanical deformation are called mechanical twins. These twins are produced in BCC and HCP metals under the conditions of decreased temperature and shock loading. Mechanical twins are not formed in FCC metals.

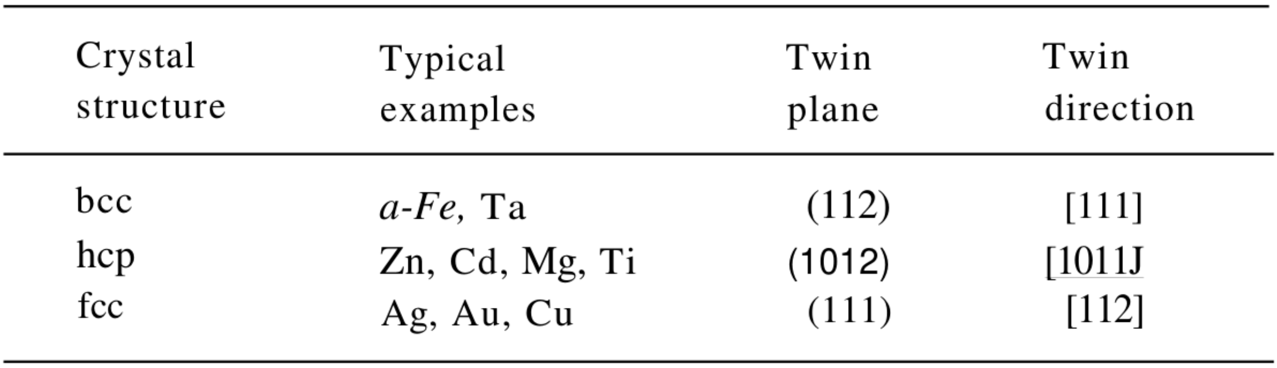
These twins can form in a few micro second time while slip takes several seconds to occur.

Annealing twins

The twins which are produced by annealing are called annealing twins. These are usually broader. Most of the FCC metals form annealing twins. They are formed because of a change in normal growth mechanism.

Twinning vs. Slip

Feature	Twinning	Slip
Mechanism	Lattice reorients by forming a mirror image	Atomic layers slide over each other
Dislocation Involvement	No dislocation motion	Dislocation motion controls slip
Occurs in	HCP, some BCC metals (low-symmetry)	FCC, BCC, HCP metals
Result	Crystal orientation changes	No change in crystal orientation
Ductility Effect	Helps deformation when slip is limited	Main deformation mechanism in ductile metals



Crystal structure	Typical examples	Twin plane	Twin direction
bcc	*a-Fe*, Ta	(112)	[111]
hcp	Zn, Cd, Mg, Ti	(1012)	[1011J
fcc	Ag, Au, Cu	(111)	[112]

Twinning generally occurs when the slip systems are restricted or when something increases the critical resolved shear stress so that the twinning stress is lower than the stress for slip. This explains the occurrence of twinning at low temperatures or high strain rates in BCC and

FCC metals or in HCP meals at orientations which are unfavorable for basal slip.

The important role of twinning in plastic deformation comes not from the strain produced by the twinning process but from the fact that orientation changes resulting from twinning may place new slip systems in a favorable orientation with respect to the stress axis so that additional slip can take place. Thus, twinning is important in the overall deformation of metals with a low number of slip systems, such as the hcp meals.

For a material to undergo **general plastic deformation**, it must have **at least 5 independent slip systems**. This is based on the **von Mises criterion (or Taylor criterion)**, which states that for a material to accommodate arbitrary shape changes under stress, a minimum of **five independent slip systems** must be available.

Slip Systems in Different Crystal Structures

Crystal Structure	Total Slip Systems	Meets Von Mises Criterion?	Ductility
FCC (Face-Centered Cubic)	12 {111}⟨110⟩	✅ Yes	**High**
BCC (Body-Centered Cubic)	Up to 48 {110}, {112}, {123} ⟨111⟩	✅ Yes	**Moderate** (T-dependent)
HCP (Hexagonal Close-Packed)	3 to 18 {0001}, {10$\bar{1}$0}, {10$\bar{1}$1}	❌ No (in most cases)	**Low** to **Moderate**

2. Deformation of Metals

When a **metal** is subjected to an external force, it undergoes **deformation**. This deformation can be **elastic** or **plastic**, depending on the amount of applied stress.

Elastic Behavior of Metals

Elastic deformation occurs when a material returns to its original shape after the applied force is removed.

Characteristics of Elastic Behavior

- **Reversible deformation** (no permanent shape change).
- Governed by **Hooke's Law**:
  $\sigma = E\varepsilon$
  Where:
  - σ = Stress (force per unit area)
  - ε = Strain (change in length/original length)
  - E = Young's modulus (elastic modulus)
- The stress-strain curve in the elastic region is **linear** (proportional relationship).
- Elastic behavior is due to **atomic bonds stretching** without breaking.

Plastic Behavior of Metals

Plastic deformation occurs when the applied force **exceeds the elastic limit**, causing permanent deformation.

Characteristics of Plastic Behavior

- **Irreversible deformation** (metal does not return to its original shape).
- Starts at the **yield point** when the stress exceeds the **yield strength**.
- Governed by **dislocation movement** in the crystal lattice.
- The stress-strain curve becomes **non-linear** beyond the elastic limit.

Comparison of Elastic & Plastic Behavior

Property	Elastic Deformation	Plastic Deformation
Reversibility	Reversible	Permanent

Property	Elastic Deformation	Plastic Deformation
Atomic Movement	Atoms stretch but return to position	Atoms slip & rearrange
Stress-Strain Curve	Linear (Hooke’s Law)	Non-linear
Limit	Up to yield strength	Beyond yield strength
Examples	Small deformations in springs, wires	Metal forging, deep drawing

Yielding Criteria

Yielding is the point where a material **transitions from elastic to plastic deformation** under applied stress. Yield criteria help determine when this transition occurs, especially under **complex loading conditions.**

Why Are Yield Criteria Important?

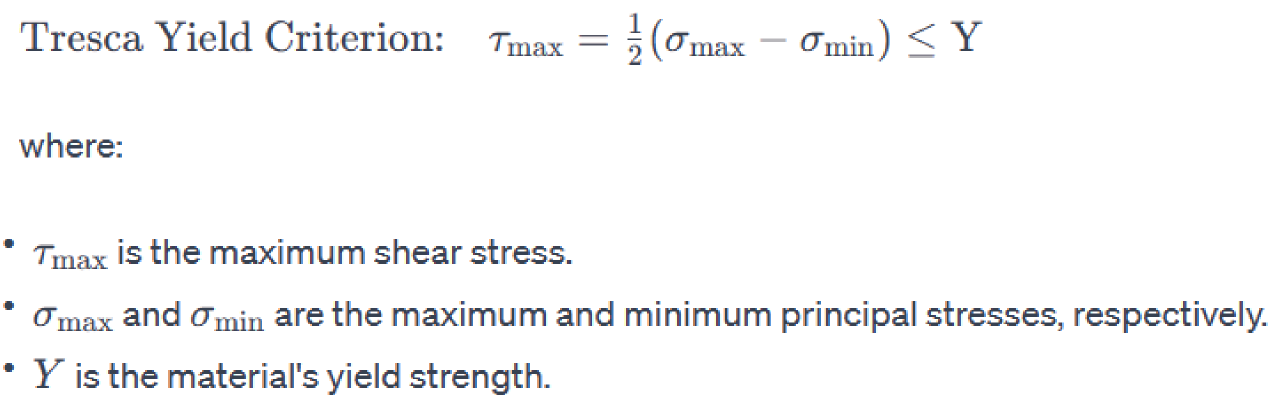
Predicts when plastic deformation begins in a material.
Ensures safety in structural design (avoiding unexpected failure).
Used in plasticity models for metal forming, stress analysis, and material selection.

Common Yield Criteria

Tresca Yield Criterion (Maximum Shear Stress Theory)

- The Tresca Criterion is based on the idea that yielding occurs when the maximum shear stress in a material reaches a critical value.
- The criterion focuses on the difference between the maximum and minimum principal stresses, and it states that yielding will occur when this difference exceeds a critical value.

Mathematically, the Tresca Criterion is expressed as follows:



$$\text{Tresca Yield Criterion:} \quad \tau_{\max} = \frac{1}{2}(\sigma_{\max} - \sigma_{\min}) \leq \text{Y}$$

where:

- $\tau_{\max}$ is the maximum shear stress.
- $\sigma_{\max}$ and $\sigma_{\min}$ are the maximum and minimum principal stresses, respectively.
- Y is the material's yield strength.

The Tresca Criterion is often used when the material's behavior is thought to be controlled primarily by its resistance to shear deformation. It is simple to apply and does not involve complex calculations compared to the von Mises criterion.

- **Simple and conservative.**
- **Less accurate for general stress states.**
- **Best for ductile materials (e.g., steel, aluminum).**
- Yielding occurs when the **maximum shear stress** reaches a critical value.

von Mises Yield Criterion (Distortion Energy Theory)

The von Mises criterion and the distortion-energy criterion are both used in the field of material science and engineering to predict the yielding of materials under various loads. These criteria are particularly relevant for ductile materials, which deform plastically before fracture.

- The von Mises criterion, also known as the maximum distortion energy criterion or the octahedral shear stress criterion, is based on the idea that yielding occurs when a certain equivalent stress (von Mises stress) reaches a critical value.
- The **von Mises stress** is a combination of **normal and shear stresses** and is expressed as an equivalent stress that represents the distortion energy in a material.
- The criterion states that yielding will occur if the von Mises stress exceeds a critical value, regardless of the individual normal and shear stress components.

$$\sigma_{\mathrm{VM}} = \sqrt{\frac{1}{2}\left((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right)}$$

where σ_1, σ_2, and σ_3 are the principal stresses.

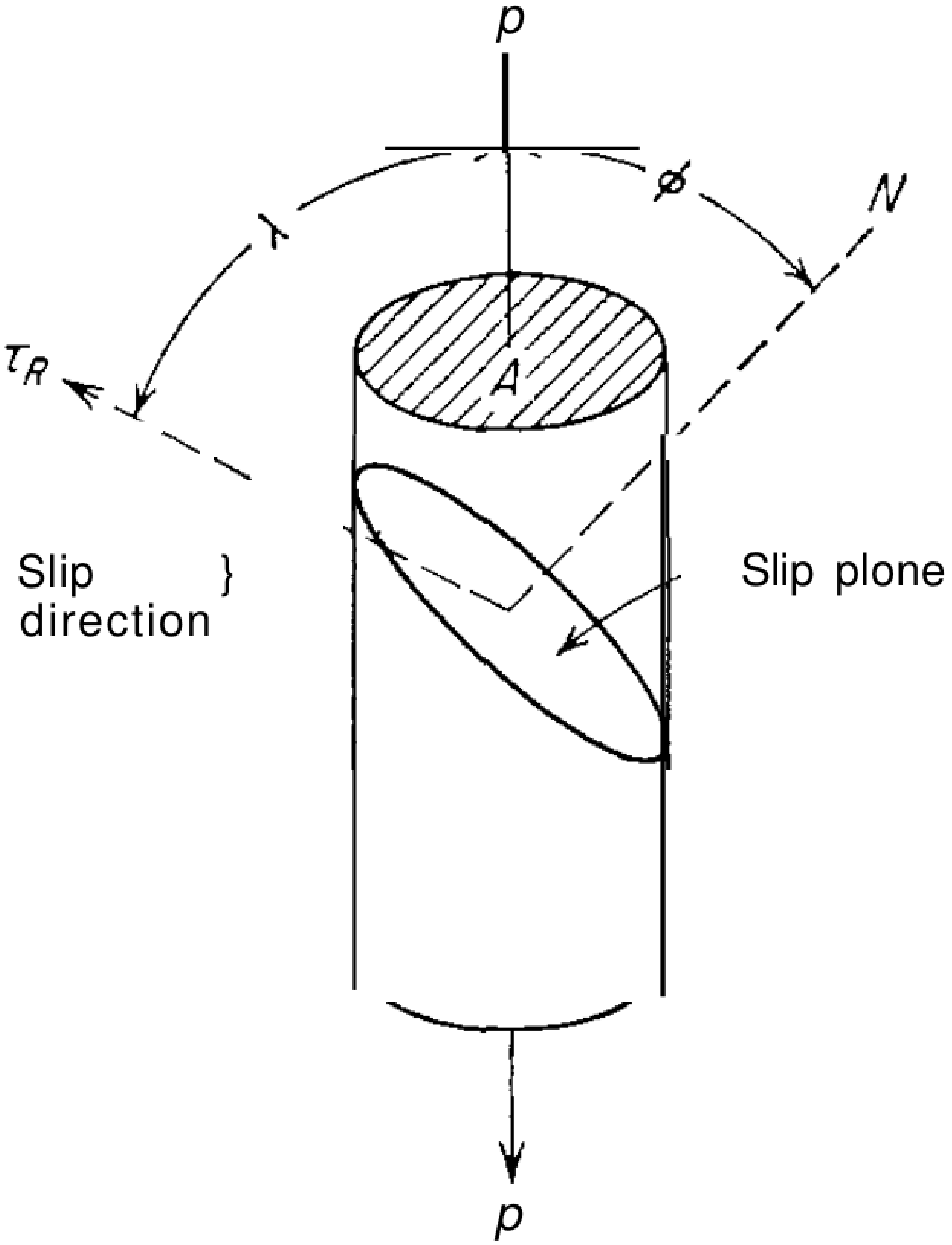
- **More accurate for ductile materials** than Tresca.
- Yielding occurs when the **distortion energy** reaches a critical value.
- **More accurate for general 3D stress states.**
- **Used in Finite Element Analysis (FEA).**
- **Slightly more complex than Tresca.**

Critically Resolved Shear Stress (CRSS)

The extent of slip in a single crystal depends on the magnitude of the shearing stress produced by external loads, the geometry of the crystal structure, and the orientation of the active slip planes with respect to the shearing stresses. Slip begins when the shearing stress on the slip plane in the slip direction reaches a threshold value called the **critical resolved shear stress**.

Consider a cylindrical single crystal with **cross-sectional area A**.

- **σ** = Applied normal stress (force per unit area).
- **τ** = Resolved shear stress on the slip plane.
- **φ** = Angle between the tensile axis and the **normal to the slip plane**.
- **λ** = Angle between the tensile axis and the **slip direction**.



The area of the slip plane is $A/\cos\phi$, because the slip plane is inclined at an angle ϕ to the tensile axis.

The component of the applied force F acting in the slip direction is $F\cos\lambda$.

Therefore, the resolved shear stress (τ_{RSS}) can be calculated as:

$$\tau_{RSS} = \frac{F\cos\lambda}{A/\cos\phi} = \frac{F\cos\lambda\cos\phi}{A}$$

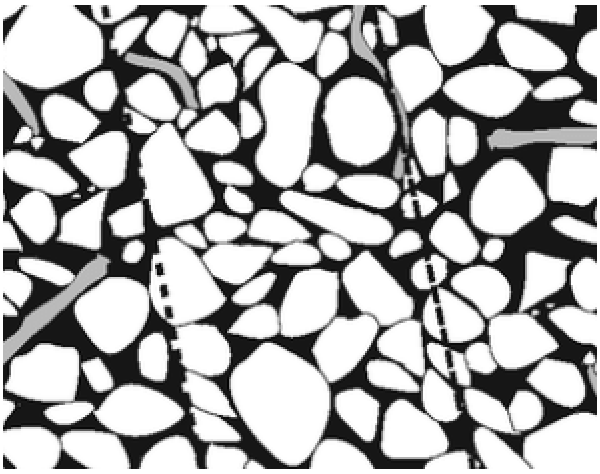
Since the applied tensile stress is $\sigma_{app} = F/A$, we can rewrite the equation for τ_{RSS} as:

$$\tau_{RSS} = \sigma_{app}\cos\phi\cos\lambda$$

- **Maximum resolved shear stress** occurs when $\varphi=\lambda=45^\circ$, giving $\tau_{max}=\sigma/2$
- **No resolved shear stress** ($\tau=0$) when the tension axis is either **normal or parallel to the slip plane**.

Deformation Bands

Deformation bands are regions within a metal's microstructure where plastic deformation is concentrated. This means that the material within these bands experiences a significantly higher level of strain compared to the surrounding material.
A key characteristic of deformation bands is that they exhibit a different crystallographic orientation compared to the matrix (the surrounding material). This change in orientation is a result of the localized plastic deformation.



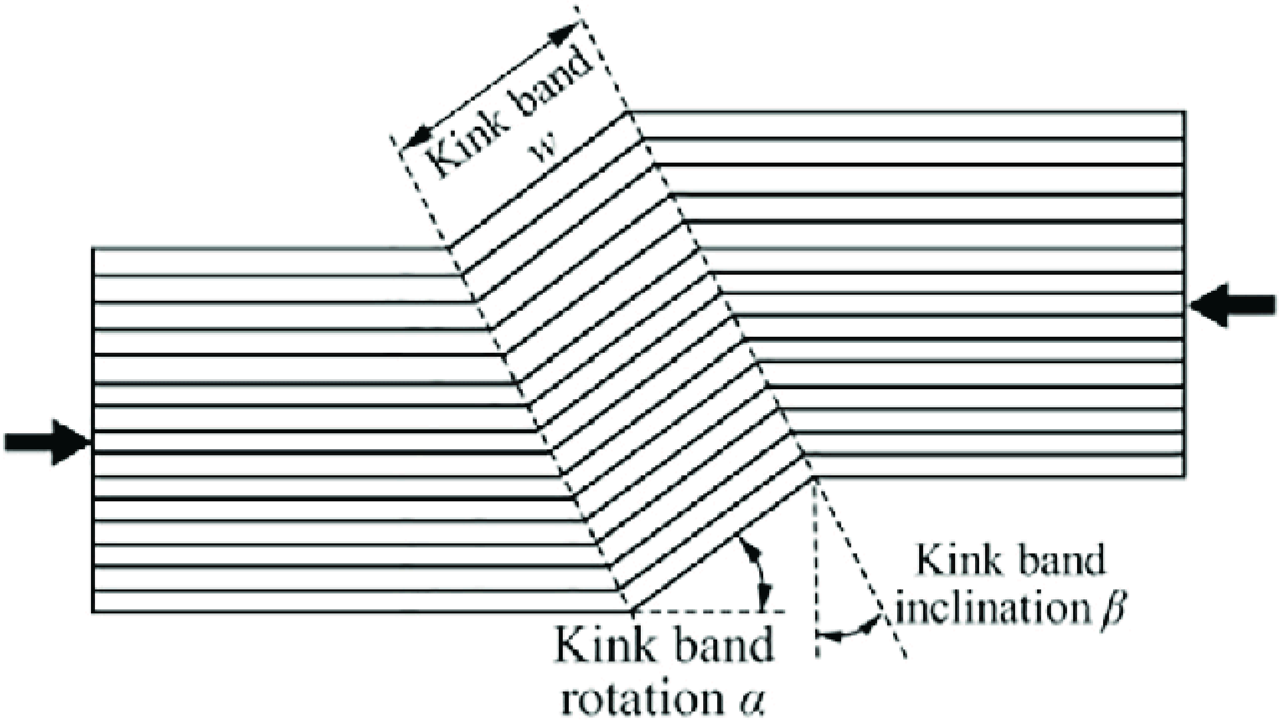
The tendency for the formation of deformation bands is greater in polycrystalline specimens because the restraints imposed by the grain boundaries make it easy for orientation differences to arise in a grain during deformation. Deformation bands generally appear irregular in shape but are elongated in the direction of principal strain.

Kink band

A **kink band** is a localized deformation feature that occurs in certain crystalline and polycrystalline materials when subjected to stress. It appears as a narrow zone where the lattice structure rotates, forming a sharp angle relative to the surrounding material.

- A kink band is a **localized region of plastic deformation** in which atomic planes or grain orientations bend abruptly.
- The material within the kink band undergoes **shear deformation**, forming a distinct boundary from the surrounding undeformed regions.

- Typically occurs in materials with **low symmetry**, such as **hexagonal close-packed (HCP) metals**, layered materials, and composites.



3. Strengthening Mechanism

It should be clear from this that strength is inversely related to dislocation mobility and that even in high-purity single crystals there are a number of possible factors that can affect the strength and mechanical behavior.

Different types of strengthening mechanisms

- Fine grain size is often desired for high strength
- Large additions of solute atoms are added to increase strength
- Bring about new phase relationships
- Fine-particles may be added to increase strength
- Phase transformations may be utilized to increase strength

Grain Boundry and Deformation

The boundaries between grains in a polycrystalline aggregate are a region of disturbed lattice only a few atomic diameters wide. In the general case, the crystallographic orientation changes abruptly in passing from one grain to the next across the grain boundary.

More slip systems are usually operative near the grain boundary, the hardness usually will be higher near the boundary than in the center of a grain.The strain hardening of a fine grain size metal will be greater than in a coarse-grain polycrystalline aggregate.

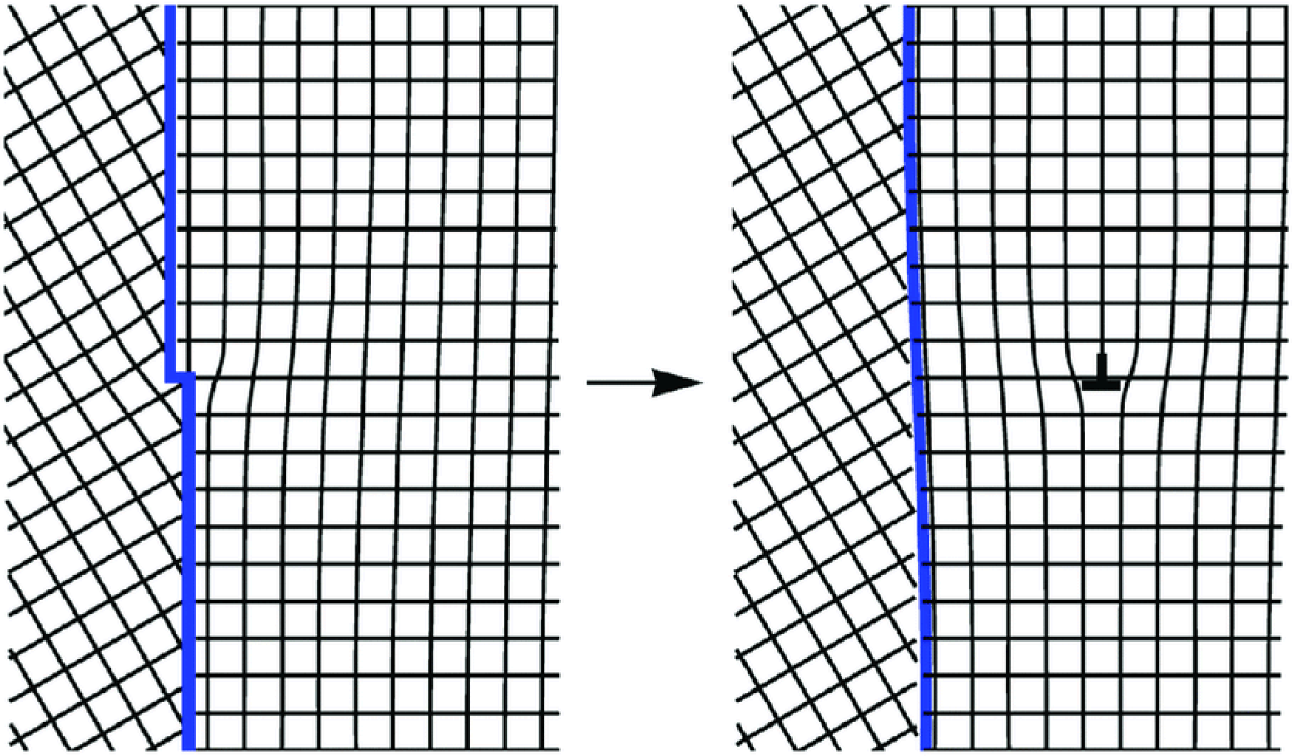
Low-Angle Grain Boundaries (LAGBs) ($\theta<15°$)

- Formed by **dislocation arrays** that accommodate small misorientations.
- Less energy than high-angle boundaries → More stable.
- Act as **barriers to dislocation motion**, affecting mechanical properties.

High-Angle Grain Boundaries (HAGBs) ($\theta>15°$)

- Random atomic arrangement → Higher energy than LAGBs.
- Major barriers to dislocation motion → Strengthens material (Hall-Petch effect).
- Facilitates **grain-boundary diffusion** and migration.

This grain boundary structure contains grain-boundary dislocations. These are not mobile dislocations producing extensive slip; rather, their chief role is that they group together within the boundary to form a step or grain-boundary ledge. As the misorientation angle of the grain boundary increases the density of the ledges increases. Grain-boundary ledges are effective sources of dislocations.



Von Mises ‘showed that for a crystal to undergo a general change of shape by slip requires the operation of five independentslip systems. Crystals which do not possess five independentslip systems are never ductile in polycrystalline form, although small plastic elongation may be obtained if there is twinning or a favorable preferred orientation.
Cubic metals easily satisfy this requirement, which accountsfor their general high ductility. Hexagonal close-packed and other low-symmetry metals do not satisfy this requirement and have low ductility at foom temperature in polycrystalline form.

At temperatures above about one-half of the melting point, deformation can occur by sliding along the grain boundaries. Grain-boundary sliding becomes more prominent with increased temperature and decreasing strain rate, as in creep.
If we want to study the Grain Boundary Sliding, we have to focus on **Equicohesive Temperture**. Above this temperature the grain boundary region is weaker than the grain interior and strength increases with increasing grain size. Below the equicohesive temperature the grain-boundary region is stronger than the grain interior and strength increases with decreasing grain size (increasing grain-boundary area).

ⓘ **Equicohesive Temperture**

> The equicohesive temperature is a critical point in the behavior of materials, particularly metals, at elevated temperatures. It refers to the specific temperature at which the strength of the grain boundaries within the material becomes equal to the strength of the individual grains themselves.

- **Fracture mode:** Below the equicohesive temperature, the grain boundaries are generally stronger than the grains. Therefore, when a material fractures under stress, the crack tends to propagate through the grains themselves, resulting in a **Transgranular Fracture**.
- **Above the equicohesive temperature:** However, as the temperature increases, the grain boundaries weaken relative to the grains. Consequently, when the material fractures under stress, the crack tends to follow the weaker path along the grain boundaries, leading to an **Intergranular Fracture**.

Strengthening from Grain Boundary

While grain boundaries can sometimes weaken materials and lead to fracture, they can also be utilized for **strengthening** under certain circumstances. This strengthening mechanism is known as **grain boundary strengthening** or **Hall-Petch strengthening**.

How it works:
Grain boundaries act as obstacles to the movement of dislocations, which are line defects that allow materials to deform. When a material is deformed, dislocations move through the crystal lattice, but they encounter difficulties when they reach a grain boundary. This difficulty arises due to several factors:

- **Misorientation:** Grains can have different crystallographic orientations. Crossing a grain boundary requires the dislocation to change its direction, which requires energy.
- **Disordered structure:** Grain boundaries have a more disordered atomic structure than the grain interiors, making it difficult for dislocations to glide smoothly through them.
- **Impurity segregation:** Sometimes, impurities or alloying elements can segregate to grain boundaries, further pinning the dislocations.

The smaller the average grain size, the more grain boundaries there are per unit area. This means more obstacles for dislocations to overcome, resulting in:

- **Increased yield strength:** The stress required to initiate plastic deformation becomes higher.
- **Improved creep resistance:** Creep is the slow, time-dependent deformation of materials at high temperatures. More grain boundaries can impede dislocation movement, making the material more resistant to creep.

Limitations:
Although grain boundary strengthening can be effective, it has limitations:

- **Decreasing returns:** As the grain size gets smaller and smaller, the strengthening effect eventually plateaus and can even start to decrease due to other factors like increased grain boundary area for diffusion and oxidation.
- **Brittle fracture:** Very small grain sizes can also make the material more brittle, as intergranular fracture becomes more likely.

Effect of High-Angle Grain Boundaries (HAGBs) on Strengthening Mechanisms

High-angle grain boundaries (HAGBs) play a crucial role in the **strengthening of materials** by obstructing dislocation motion. This effect is fundamental to several strengthening mechanisms, particularly **grain-boundary strengthening (Hall-Petch effect)**.

How HAGBs Strengthen Materials

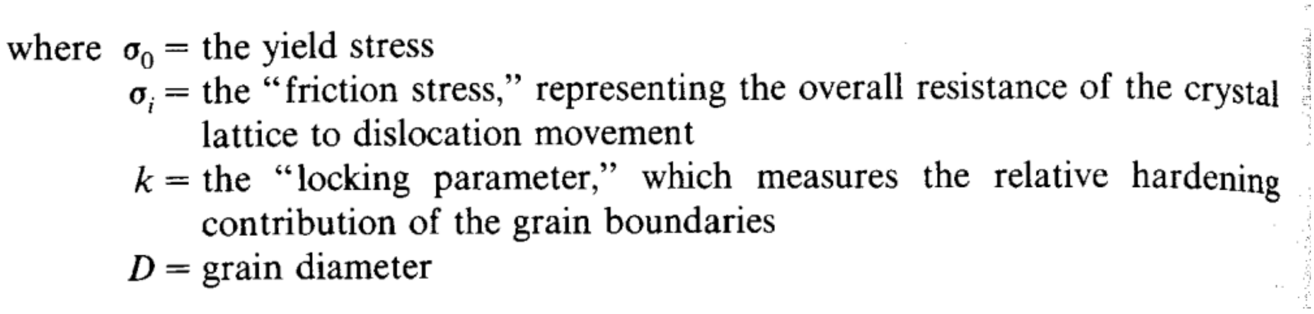
HAGBs Act as Barriers to Dislocation Motion

- Dislocations are the primary carriers of plastic deformation.
- When a dislocation moves, it encounters grain boundaries.
- **In HAGBs ($\theta > 15°$), the atomic arrangement is highly misoriented**, making it difficult for dislocations to pass through.
- This increases the applied stress required for deformation → **Stronger material.**

Hall-Petch Strengthening (Grain-Boundary Strengthening)

Hall-Petch Equation:

$$\sigma_0 = \sigma_i + kD^{-1/2}$$



where σ_0 = the yield stress

σ_i = the "friction stress," representing the overall resistance of the crystal lattice to dislocation movement

k = the "locking parameter," which measures the relative hardening contribution of the grain boundaries

D = grain diameter

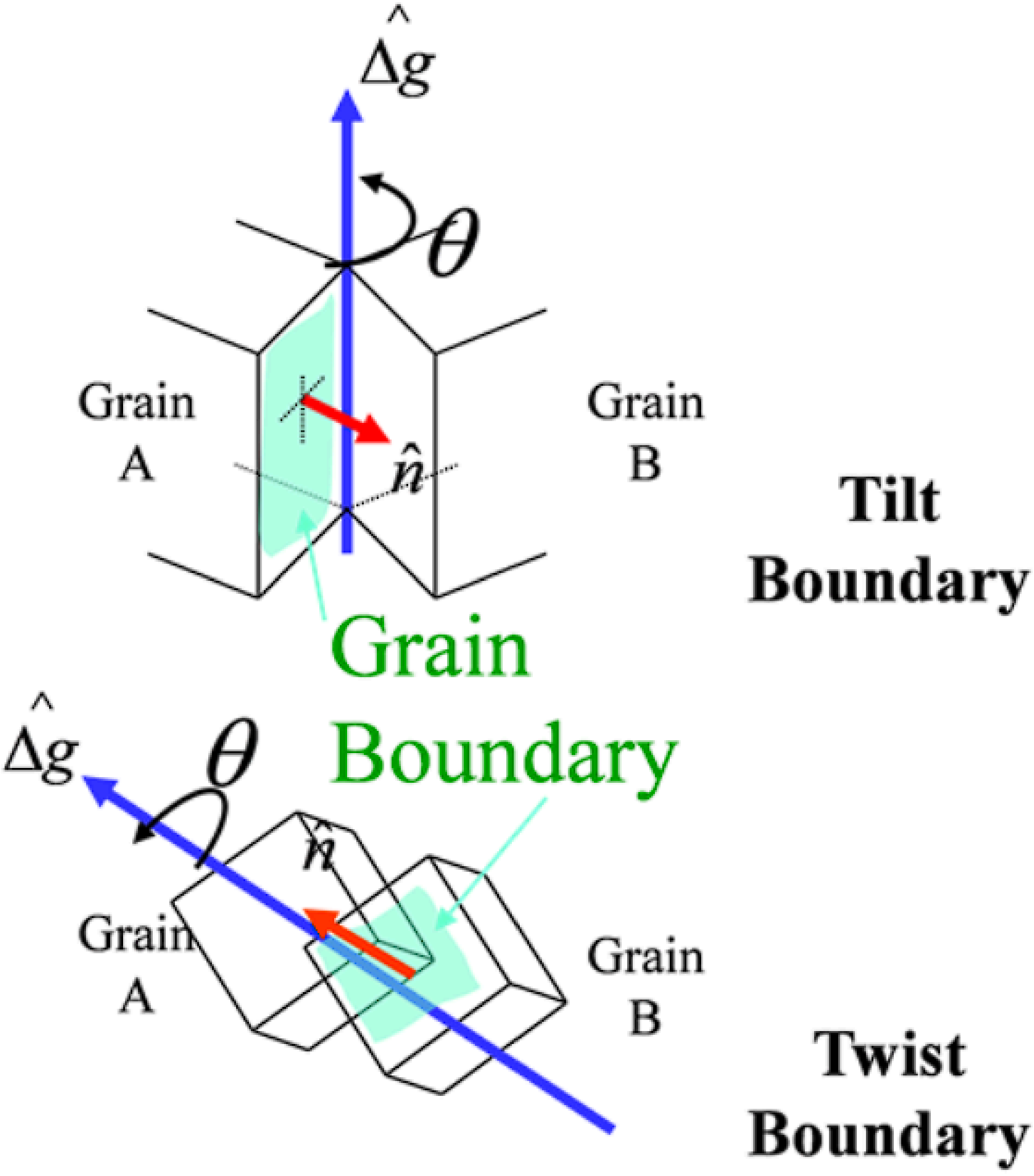
- **Smaller grains = More HAGBs = Higher Strength**
- Fine-grained steels and aluminum alloys are stronger than coarse-grained counterparts.

Work Hardening & Dislocation Pile-Up at HAGBs

- Dislocations accumulate at HAGBs since they **cannot easily cross the boundary**.
- This pile-up creates **local stress concentrations**, making further deformation difficult.
- The material **work-hardens**, meaning it becomes stronger as deformation progresses.

Effect of Low Angle Grain Boundary (LAGBs) on Strengthening Mechanisms

A low-angle grain boundary (LAGB) is a type of defect in a crystalline material where two neighboring grains have a slightly different crystallographic orientation. The misorientation angle between the two grains is typically less than 15 degrees. LAGBs are important because they can significantly affect the properties of materials, such as their strength, ductility, and conductivity.



There are two main types of LAGBs:

Twist Boundaries

- **Rotation axis: Perpendicular** to the boundary plane
- **Dislocation type:** Screw dislocations
- **Example:** Rotating a book on a table (axis ⊥ surface)

Tilt Boundaries

- **Rotation axis: Parallel** to the boundary plane
- **Dislocation type:** Edge dislocations
- **Example:** Tilting a picture frame on a wall (axis ∥ wall surface)

This misalignment can be caused by various mechanisms, including:

Plastic deformation:

- When a material is deformed, the individual grains can rotate slightly to accommodate the strain. This can lead to the formation of LAGBs.
  Deposition:
- During the deposition of thin films, the atoms can arrive at the substrate with a slight misorientation, leading to the formation of LAGBs.
  Phase transformations:
- When a material undergoes a phase transformation, the new phase may have a slightly different orientation than the parent phase. This can also lead to the formation of LAGBs.
- Perhaps the most general method of producing a substructure network is by introducing a small amountof deformation (from about 1 to 10 percent prestrain) and following this with an annealing treatment to rearrange the dislocations into subgrain boundaries.
- The process of **Polygonization** will help to create a network of subgrain boundaries within a material

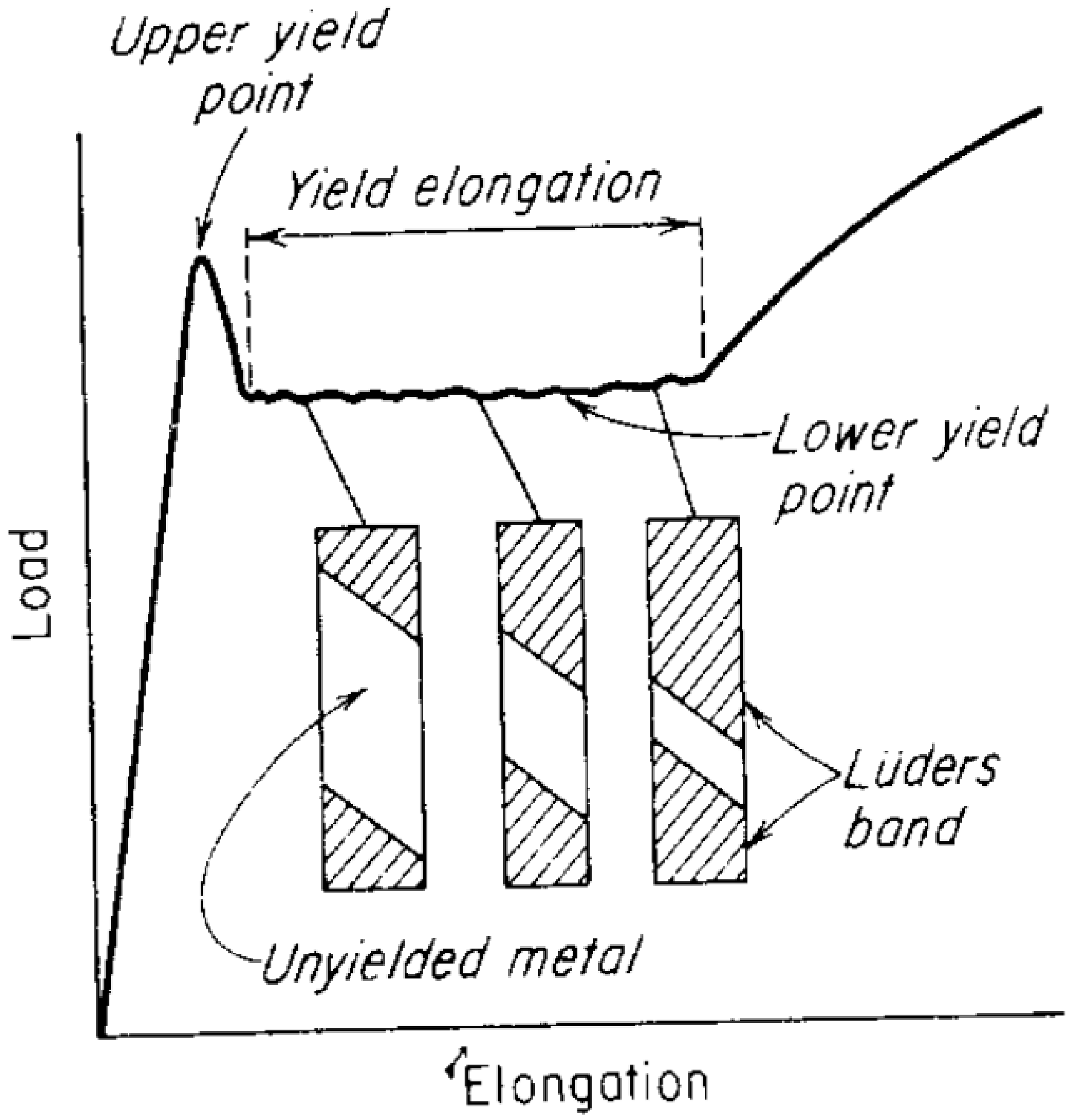
Polygonization

Polygonization is a process that is used to create a network of subgrain boundaries within a material. These subgrain boundaries are essentially low-angle grain boundaries, which means that they are boundaries between two grains that have a very small misorientation. The process of polygonization is typically carried out by following these steps:

- Introduce a small amount of deformation (typically 1-10%) into the material. This deformation creates dislocations, which are line defects in the crystal structure of the material.
- Anneal the material at a temperature that is high enough for the dislocations to move, but low enough to prevent the formation of new grains. During annealing, the dislocations will rearrange themselves into subgrain boundaries.

Yield Point Phenomenon

The yield point phenomenon is an interesting occurrence observed in certain materials, primarily low-carbon steels, during tensile testing. It produces a unique feature on the stress-strain curve, marked by a sudden drop in stress followed by a plateau of constant stress while the strain continues to increase. This is commonly observed in low-carbon steels and some other metals like titanium and aluminum alloys.



Key Features:

Sudden Stress Drop:

- At the yield point, the material experiences a sudden decrease in stress even though the deformation (strain) continues.
- The point where the drop happens is call **Upper Yield Point**
- This drop can be significant, ranging from 5% to 30% of the peak stress.

  Yield Point Elongation:
- The constant stress plateau corresponds to a measurable increase in strain (elongation) without requiring additional force. This phenomenon is termed **yield point elongation**.

  Strain Hardening:

- After the plateau, further strain increase leads to rising stress due to strain hardening, where the material resists deformation more efficiently.

The deformation occuring throughout the yield point eleongation is heterogenious.
At the upper yield point a discrete band of deformed metal, often readily visible with the eye, appears at a stress concentration such as a fillet, and coincident with the
formation of the band the load drops to- the lower yield point. The band then
propagates along the length of the specimen, causing the yield-point elongation.
In the usual case several bands will form at several points of stress concentration.
These bands are generally at approximately 45° to the tensile axis. They are usually called **Luders bands**.

> **Luders bands**
>
> Lüders bands, also known as stretcher-strain marks or slip bands, are localized bands of plastic deformation in metals experiencing tensile stresses. They are common in low-carbon steels and certain Al-Mg alloys.
> **Formation:**
> Lüders bands form when the stress applied to a metal exceeds the yield strength. At this point, the metal begins to deform plastically, meaning that it will not return to its original shape when the stress is removed. The Lüders bands are formed as a result of the movement of dislocations, which are line defects in the crystal structure of the metal.

Mechanism Behind Yield-Point Phenomenon (YPP):

- **Dislocation Pinning by Solutes or Impurities:**
    - In many materials, dislocations are initially pinned by solute atoms (e.g., carbon or nitrogen in steel).
    - These solutes segregate around dislocations and form Cottrell atmospheres, preventing dislocation motion.
- **Elastic Deformation Phase:**
    - As stress increases during elastic loading, dislocations remain trapped by solute atoms.

  - The applied stress must reach a critical value to break the pinning effect.
- **Sudden Yielding (Upper Yield Point):**
  - Once the critical stress is reached, dislocations break free from their solute atmospheres.
  - This results in a sudden and localized plastic deformation, leading to the sharp drop in stress known as the **upper yield point**.
- **Propagation of Lüders Bands:**
  - After yielding starts, plastic deformation propagates through the material in bands called **Lüders bands**.
  - These bands move through the material at a nearly constant stress, creating the plateau in the stress-strain curve (Lower Yield Point region).
- **Work Hardening Resumes:**
  - Once **Lüders bands** have fully propagated, normal strain hardening begins, and the material behaves as expected in further plastic deformation.

Strain Aging

Strain aging is a type of behavior, usually associated with the yield-point phenomenon,in which the strength of a metal is increased and the ductility is decreased on heating at a relatively low temperature after cold-working.

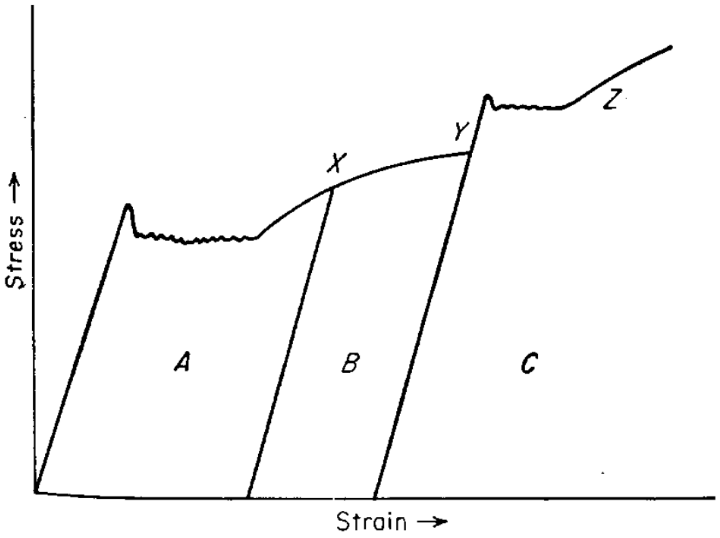


Figure 6-9 Stress-strain curves for low-carbon steel showing strain aging. Region *A*, original material strained through yield point. Region *B*, immediately retested after reaching point *X*. Region *C*, reappearance and increase in yield point after aging at 400 K (≈ 130°C).

Step-by-Step Process of Strain Aging

- **Plastic Deformation (Strain Introduction):**
  - When a material (e.g., low-carbon steel) is plastically deformed, **dislocations** are introduced.

    - Some dislocations move freely, while others interact with solute atoms present in the metal.
- **Diffusion of Solute Atoms (Aging Begins):**
    - Over time or under elevated temperatures, **carbon and nitrogen atoms diffuse** toward dislocations.
    - These interstitial atoms form **Cottrell atmospheres**, pinning the dislocations and restricting their movement.
- **Dislocation Pinning (Increased Strength):**
    - As solute atoms cluster around dislocations, higher stress is required to move them again.
    - This results in an **increase in yield strength** (hardening effect).
- **Decreased Ductility & Toughness:**
    - Since dislocations are locked, the material becomes **less ductile** and more **brittle.**
    - Lüders bands (strain localization) appear when the material is reloaded.
- **Formation of Serrated Stress-Strain Curve (Dynamic Strain Aging):**
    - If the material is **continuously deformed at elevated temperatures** (~200–400°C), solutes pin moving dislocations intermittently.
    - This results in a **jerky or serrated flow** in the stress-strain curve (Portevin-Le Chatelier effect).

> ⓘ Strain Aging
>
> To control strain aging,it is usually desirable to lower the amount of carbon and nitrogen in solution by adding elements which will take part of the interstitials out of solution by forming stable carbides or nitrides.

Types of Strain Aging:

- **Static Strain Aging (After Deformation, at Rest):**
    - Happens when a deformed material is left at room or slightly elevated temperatures.
    - Solute atoms diffuse and lock dislocations over time, leading to higher yield strength and lower ductility.
- **Dynamic Strain Aging (During Deformation at High Temperatures):**
    - Occurs during plastic deformation at **200–400°C**.
    - Solute atoms diffuse **while dislocations are moving**, causing intermittent pinning and serrated flow in the stress-strain curve.
    - Leads to **blue brittleness** in steels.

To control strain aging, it is usually desirable to lower the amount of carbon and nitrogen in
solution by adding elements which will take part of the interstitials out of solution
by forming stable carbides or nitrides. Aluminum, vanadium, titaniun,
columbium, and boron have been added for this purpose. While a certain amount of
control over strain aging can be achieved, there is no commercial low-carbon steel
which is completely non-strain aging.

Factors Influencing Strain Aging:

- **Chemical composition:** The presence and type of solute atoms play a crucial role. Materials with higher concentrations of elements like carbon and nitrogen are more susceptible to strain aging.
- **Deformation level:** The extent of plastic deformation also impacts the severity of strain aging. Higher degrees of deformation lead to more dislocations and, consequently, more solute atom interaction, resulting in greater strength increase and ductility loss.
- **Aging temperature and time:** The temperature and duration of aging determine how quickly and extensively the solute atoms diffuse and interact with dislocations. Higher temperatures and longer durations generally lead to stronger aging effects.

Quench Aging

Quench aging is a phenomenon that occurs when a metal, typically steel or aluminum alloys, is rapidly cooled (**quenched**) from a high temperature and then undergoes aging due to the diffusion of solute atoms to dislocations. This process results in an increase in strength and hardness but a reduction in ductility.

Mechanism of Quench Aging

- **Quenching (Rapid Cooling):**
  - The material is heated to a high temperature (e.g., in the austenitic range for steel) and then rapidly cooled.
  - This prevents the equilibrium precipitation of solute atoms (like carbon and nitrogen in steel) and **freezes them in a supersaturated solid solution**.
- **Aging (Diffusion of Solute Atoms):**
  - When the quenched material is **left at room temperature (natural aging) or reheated at a moderate temperature (artificial aging),**

solute atoms start diffusing.
  - These atoms move toward dislocations and form **Cottrell atmospheres**, pinning the dislocations and increasing strength.
- **Increased Yield Strength & Hardness:**
  - As dislocations become pinned by solute atoms, more stress is required to move them, leading to a **higher yield strength**.
  - However, this also reduces the material's ductility and toughness.

Solid Solution Strenghtening

The introduction of solute atoms into solid solution in the solvent-atom lattice invariably produces an alloy which is stronger than the pure metal.
There are two types of solid solutions.

- If the solute and solvent atoms are roughly similarin size, the solute atoms will occupy lattice points in the crystal lattice of the solvent atoms. This is called Substitutional solid solution.
- If the solute atoms are much smaller than the solvent atoms, they occupy interstitial positions in the solvent lattice. Carbon, nitrogen, oxygen, hydrogen, and boron are the elements which commonly form Interstitial solid solutions.

The factors which control the tendency for the formation of substitutional solid solutions have been uncovered chiefly through the work of Hume-Rothery. We call this as **Hume Rothery Rule**.

ⓘ **Hume Rothery Rule**

Several factors influence the formation and extent of substitutional solid solutions, where solute atoms replace solvent atoms in a crystal lattice. Here are the key ones:
1. Atomic Size: This is the most crucial factor. For a strong, stable solution, the size difference between the solute and solvent atoms should be **less than 15%**. Larger size differences distort the lattice, introducing strain and hindering further substitution.
2. Crystal Structure: Solute and solvent atoms should have **similar crystal structures**. This allows for easier incorporation of solute atoms into the solvent lattice without major disruptions.
3. Electronegativity: Close electronegativity values between solute and solvent promote metallic bonding and stable solutions. Large differences indicate potential ionic character and intermetallic compound formation instead of true solid solutions.
4. Valence: Ideally, solutes and solvents should have the **same**

valence. This ensures balanced charges and avoids charge imbalances that can disturb the lattice. However, sometimes, solutions form with a difference in valence, potentially leading to ordered structures or defect compensation mechanisms.
5. Temperature: Higher temperatures provide thermal energy, helping overcome size and energy barriers for solute atoms to enter the lattice, leading to **increased solubility** and a wider range of possible solutions.

Solute atoms can interact with dislocations by the following mechanisms: Of these various mechanisms, ***the elastic interaction, modulus interaction, and long-range order interaction*** are long range, i.e., they are relatively insensitive to temperature and continue to act to ***about 0.6 of Melting Temperture.***

- **Elastic interaction**
  - **Lattice Distortion Due to Size Mismatch:**
    - Solute atoms with a different atomic radius than the solvent atoms cause **local strain fields** in the lattice.
    - If a solute atom is **larger** than the surrounding solvent atoms, it creates **compressive strain**; if it is **smaller**, it creates **tensile strain.**
    - These strain fields interact with the stress field of dislocations, particularly with edge dislocations.
  - **Interaction with Edge Dislocations:**
    - Edge dislocations have **compressive stress above the extra half-plane** and **tensile stress below.**
    - Solute atoms tend to diffuse toward the region where they **reduce the overall strain energy**:
      - **Smaller solute atoms** migrate to **compressive regions** (above the extra plane).
      - **Larger solute atoms** migrate to **tensile regions** (below the extra plane).
    - This forms a **Cottrell atmosphere**, which **pins the dislocation** and increases the yield strength.
  - **Interaction with Screw Dislocations:**
    - Screw dislocations produce a **shear stress field** rather than a dilation/compression field.
    - The interaction with solute atoms is weaker compared to edge dislocations.
- **Modulus interaction**

    - **Elastic Inhomogeneity:**
        - Solute atoms generally have a different elastic modulus than the host metal atoms.
            - When a solute atom replaces or is embedded in the lattice, it creates a **local elastic distortion**.
    - **Energy Consideration:**
        - The presence of a dislocation changes the **local stress field**, altering the elastic energy around it.
        - If a solute atom has a **lower modulus** than the matrix, it prefers regions of **low stress** (like the dislocation core).
        - If a solute atom has a **higher modulus**, it prefers regions of **high stress** to minimize system energy.
- **Stacking-fault interaction**
    - This arise because solute atoms preferentially segregate to the stacking faults contained in extended dislocations.
    - For this to happen the solute must have a preferential solubility in the hcp structure of the stacking fault.
    - **Higher stacking fault energy:** Makes dislocation movement easier, potentially leading to softening.
        - **Lower stacking fault energy:** Discourages dislocation movement and dissociation, contributing to strengthening.

- **Electrical interaction**
    - This arises from the fact that some of the charge associated with solute atoms of dissimilar valence remains localized around the solute atom. The solute atoms become charge centers and can interact with dislocations which have electrical dipoles.
    - The electrical interaction of solute atoms is much weaker than the elastic and modulus interaction, and becomes important only whenthere is a large valence difference between solute and matrix and the elastic misfit is small.

- **Short-range order interaction**
    - This arises from the tendency for solute atoms to arrange themselves so that they have more than the equilibrium number of disimilar neighbors.
    - Strengthening occurs because the movement of a dislocation through a region of short-range order or clustering reduces the degree of local order.
- **Long-range order interaction**
    - When LRO is present, the interaction between solutes and dislocations becomes more complex.

- The superlattice itself creates a periodic stress field that can attract or repel solutes depending on their size and chemical nature.
- This long-range interaction influences the solute distribution around dislocations, affecting their mobility and strengthening effect.

Strengthening from Fine Particle

Small second-phase particles distributed in a ductile matrix are a common source of alloy strengthening. In dispersion hardening the hard particles are mixed with matrix powder and consolidated and processed by powder metallurgy techniques. However, very many alloy systems can be strengthened by precipitation reactions in the solid state.

Precipitation hardening

- Precipitation hardening, or age hardening,' is produced by solution treating and quenching an alloy in which a second phase is in solid solution at the elevated temperature but precipitates upon quenching and aging at a lower temperature.
- For Precipitation hardening to occur, the second phase must be soluble at an elevated temperature but must exhibit decreasing solubility with decreasing temperature.
- Usually there is atomic matching, or coherency, between the lattices of the precipitate and the matrix.
- The formation of a **Coherent Precipitate** in a precipitation-hardening system, such as Al-Cu, occurs in a number of steps. After quenching from solid solution the alloy contains regions of solute segregation, or clustering. Guiner and Preston first detected this local clustering with special x-ray techniques, and therefore this structure is known as a **GP zone**

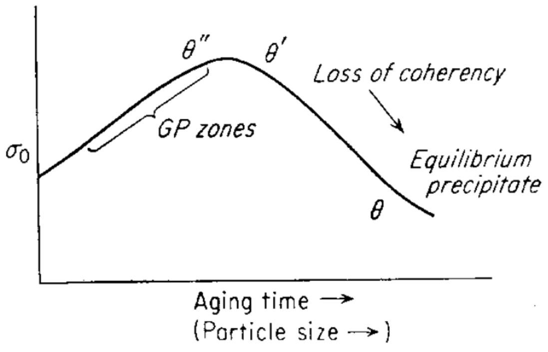


Figure 6-18 Variation of yield stress with aging time (schematic).

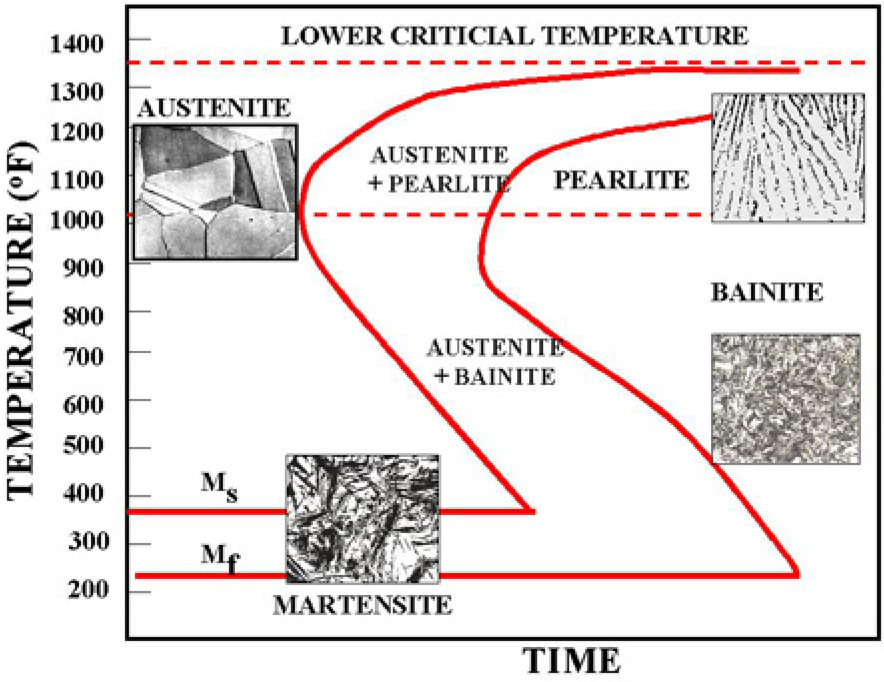
ⓘ Coherent Precipitate

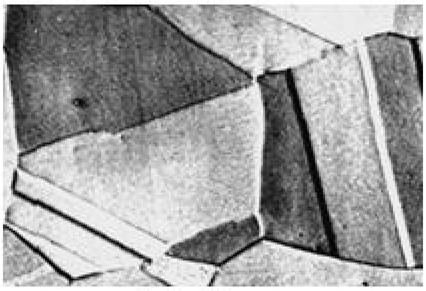
> A coherent precipitate is a type of precipitate in a material where the crystal lattice of the precipitate is perfectly aligned with the crystal lattice of the surrounding matrix. This means that the atoms in the precipitate and the matrix are arranged in the same way, with no mismatch or discontinuity at the interface between them.

Fiber Strengthening

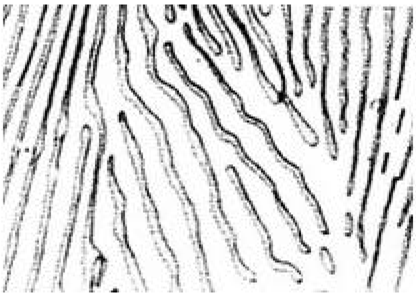
- Materials of high strength, and especially high strength-to-weight ratio, can be roduced by incorporating fine fibers in a ductile matrix. The fibers must have **high strength and high elastic modulus** while the matrix must be ductile and nonreactive with the fibers.
- Glass-fiber-reinforced polymers are the most common fiber-strengthened materials.
- In fiber strengthening the high modulus **fibers carry essentially all of the load**. The matrix serves to transmit the load to the fibers, to protect fibers from surface damage, and to separate the individual fibers and blunt cracks which arise from fiber breakage.

Martensitic Strengthening





Austenite



Pearlite

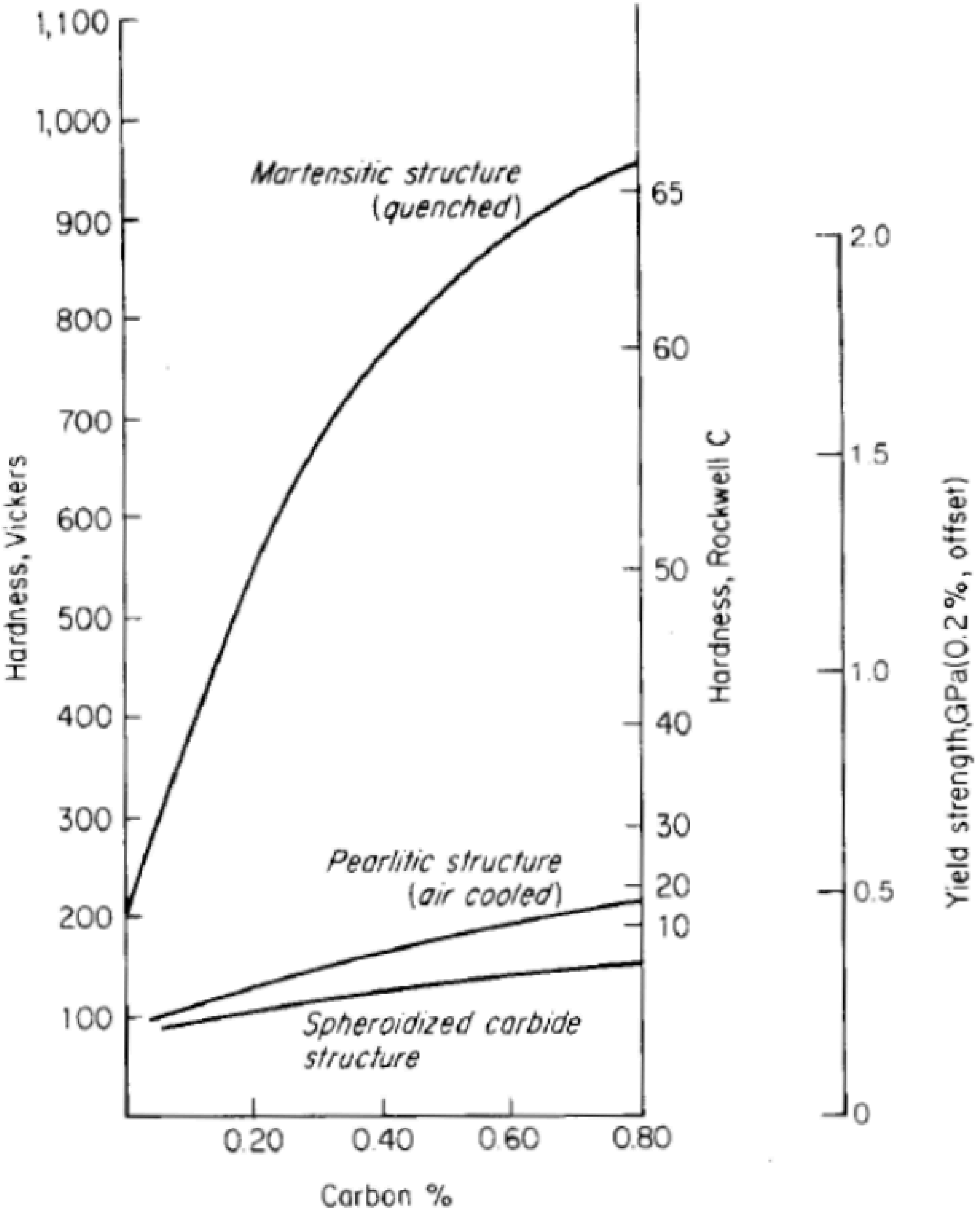
Martensite

Bainite

The transformation of austenite to martensite by a diffusionless shear-type transformation in quenching of steel is one of the most common strengthening processes used in engineering materials.
The Strenghtening of Martensite comes from

- **Solid-solution hardening:**
  - During the rapid cooling process, carbon atoms become trapped in the martensite's crystal structure, unable to diffuse out and form separate carbides. This "supersaturation" of carbon creates strain within the lattice, making it harder for dislocations (defects in the crystal structure) to move, ultimately increasing the material's strength.

- **High dislocation density:**
    - The rapid transformation from austenite to martensite also introduces a high number of dislocations into the crystal structure. These dislocations act as barriers to further slip, making it more difficult for the material to deform and further strengthening it.
- **Fine twin structure:**
    - In some cases, the martensite transformation can produce a fine twinned microstructure. These twins are essentially regions of the crystal lattice that have been sheared in a specific way, introducing additional interfaces that impede dislocation movement and contribute to strength.
- **Carbide precipitation:**
    - Although primarily associated with tempering (a secondary heat treatment), small carbide precipitates can form within the martensite at room temperature over time. These precipitates further hinder dislocation movement and can slightly increase strength, but can also reduce toughness.



Strain Hardening (Work Hardening)

Strain hardening, also known as **work hardening**, is the phenomenon where a metal becomes **stronger and harder** as it undergoes plastic deformation. This occurs because the motion of dislocations is increasingly hindered by interactions with other dislocations and lattice defects.

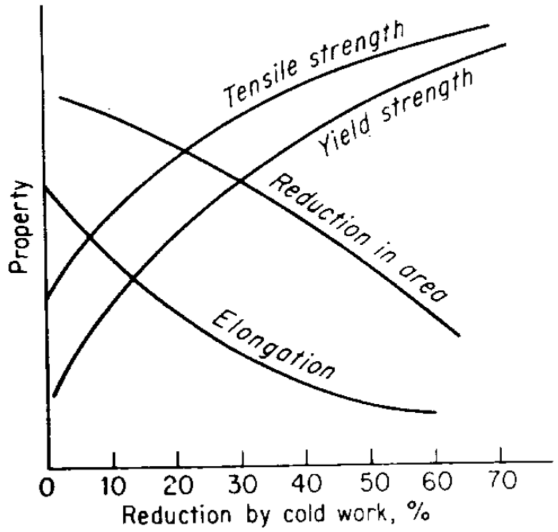


Figure 6-29 Variation of tensile properties with amount of cold-work.

- **Cold-work produces elongation of the grains in the principal direction of working.**
- An annealed metal contains about 10^4 to 10^6 dislocations per mm^2, while a severely plastically deformed metal contains about 10^{10} mm^2.

There is usually a small **decrease in density** of the order of a few tenths of a percent, an appreciable **decrease in electrical conductivity** due to an increased number of scattering centers, and a **small increase in the thermal coefficient of expansion**. Because of the **increased internal energy** of the cold-worked state, **chemical reactivity is increased**. This leads to a general **decrease in corrosion resistance** and in certain alloys introduces the possibility of stress-corrosion cracking.

Bauschinger's effect

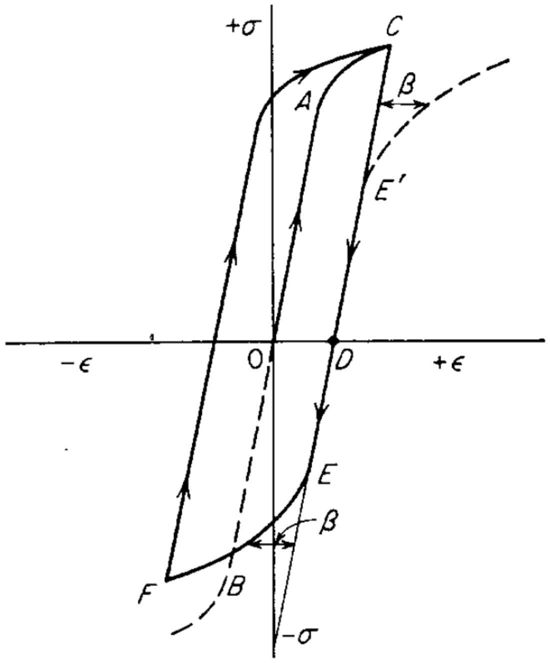


Figure 6-32 Bauschinger effect and hysteresis loop.

Generally a lower stress is required to reverse the direction of slip on a

certain slip plane than to continue slip in the original direction. The directionality of strain hardening is called the Bauschinger effect.
The solid line shows the tension test and the doted line shows the compression test. Bauschingereffect is by the Bauschinger strain. This is the difference in strain between the tension and compression curves at a given stress.
The mechanism of the Bauschinger effect lies in the structure of the cold-worked state.

During plastic deformation dislocations will accumulate at barriers in tangles, and eventually form cells. Now, when the load is removed, the dislocation lines will not move appreciably because the structure is mechanically stable. However, when the direction of loading reversed, some dislocation lines can move an appreciable distance at a low shearis stress because the barriers to the rear of the dislocations are not likely to be so strong and closely spaced as those immediately in front. This gives rise to initial yielding at a lower stress level when the loading direction is reversed.

Mechanism of the Bauschinger Effect:

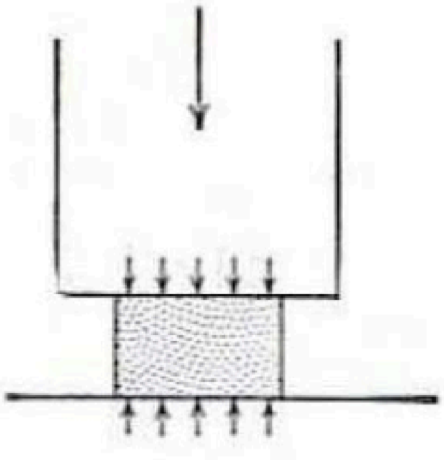
- **Initial Plastic Deformation:**
  - When a material is loaded beyond its **elastic limit**, plastic deformation occurs due to the motion of **dislocations** in a specific direction.
- **Dislocation Accumulation & Internal Stresses:**
  - As the material deforms, **dislocations accumulate** at obstacles like grain boundaries or other dislocations, creating **residual stresses**.
- **Reverse Loading:**
  - If the load is reversed, the **opposite motion of dislocations is easier** due to the pre-existing internal stresses.
  - This causes the material to yield at a **lower stress** in the opposite direction than in the original loading direction.

4. Fundamentals of Metal working

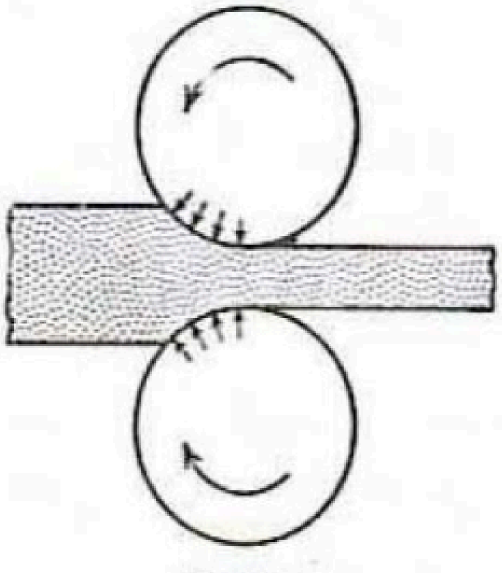
Classification of Metal working Processes

Based on Type of Force Applied

Direct compression type processes
The applied force is normal to the direction of the metal flow in compression, i.e., forging and rolling processes.

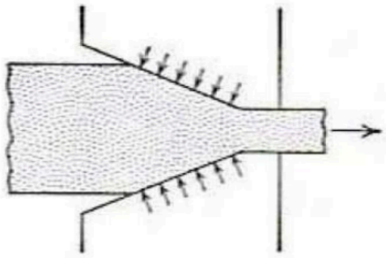


Forging

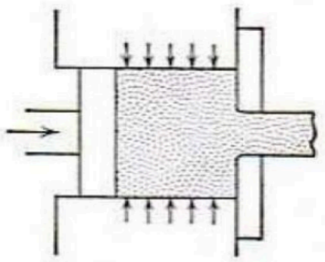


Rolling

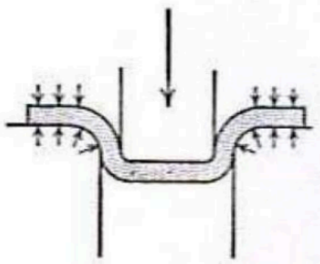
Indirect compression type processes
The primary forces are frequently tensile, with indirect compressive forces developed by the reaction of the work piece. The metal flow is therefore under the combined stress state, i.e., extrusion, wiredrawing, tube drawing.



Wire drawing

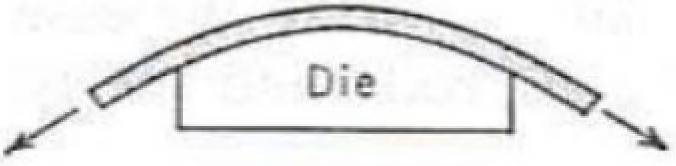


Extrusion



Deep drawing

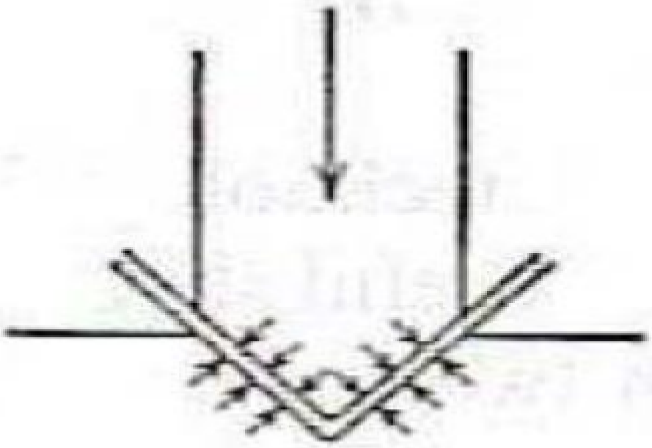
Tension type process
he applied force is tensile, i.e., stretch forming.



Stretch forming

Bending processes:

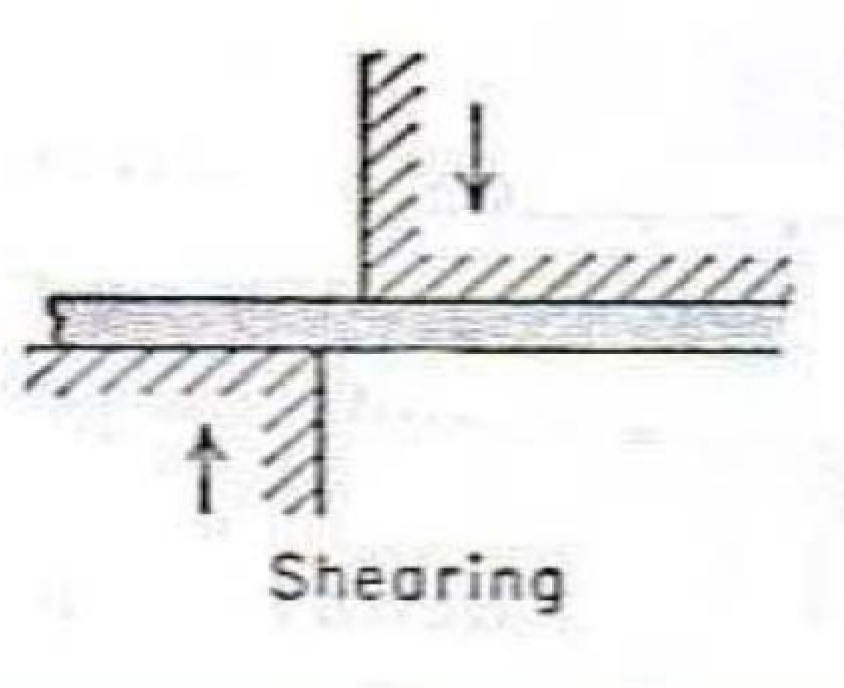
The applied force involves the application of bending moments to the sheet.



Bending

Shearing process

The applied force involves the application of shearing forces of sufficient magnitude to rupture the metal in the plane of shear.



Cold Working

Cold working, also known as **cold deformation** or **work hardening**, is a metalworking process where a metal is plastically deformed **below its recrystallization temperature**, usually at **room temperature**. It increases **strength, hardness, and surface finish** while reducing ductility.

Advantages of Cold Working

- **No Heating Required**: Cold working does not require heating, which simplifies the process and reduces energy costs.
- **Improved Surface Finish**: The process generally results in a superior surface finish compared to hot working methods.
- **Dimensional Control**: Cold working provides better dimensional accuracy and reproducibility of parts.
- **Increased Strength**: The process enhances the material's strength through work hardening, which can significantly increase tensile and fatigue strength
- **Material Efficiency**: Cold working reduces material waste compared to machining methods, especially in large production runs

Disadvantages of Cold Working

- **Higher Forces Required**: The process necessitates greater force for deformation due to increased hardness, which may require more powerful machinery and tools

- **Reduced Ductility**: Cold worked materials exhibit decreased ductility and malleability, limiting the extent of deformation achievable without cracking.
- **Residual Stress**: The process can introduce undesirable residual stresses and anisotropic properties in the final product
- **Springback Effect**: After deformation, materials may exhibit a tendency to return slightly to their original shape, known as springback

Hot Working

Hot working is a metalworking process that involves the plastic deformation of metals at temperatures above their recrystallization point. This technique allows metals to become more malleable, facilitating significant shaping without the risk of cracking or fracture, which can occur at lower temperatures.

Key Characteristics of Hot Working

- **Temperature Range**: Hot working is typically performed at temperatures ranging from 40% to 60% of the metal's melting point, ensuring that the material remains ductile and can undergo substantial deformation without hardening due to strain
- **Recrystallization**: During hot working, the metal undergoes recrystallization, which prevents strain hardening and maintains high ductility. This process results in the formation of new, smaller grains that enhance the material's mechanical properties[

Advantages of Hot Working

- **Reduced Deformation Forces**: The elevated temperatures allow for easier deformation with less force compared to cold working processes
- **Improved Ductility**: Metals retain high ductility during hot working, making them less likely to crack under stress
- **Homogeneous Microstructure**: The recrystallization process leads to a uniform grain structure, enhancing mechanical properties and reducing anisotropy
- **Efficiency for Large Components**: Hot working is particularly effective for producing large components due to its ability to handle significant material flow and deformation rates

Disadvantages of Hot Working

- **Oxidation Risk**: Metals can be prone to oxidation at elevated temperatures, which may affect surface quality and mechanical properties

- **Higher Energy Costs**: The energy required for heating metals can make hot working more expensive than cold working methods
- **Limited Material Suitability**: Not all metals are suitable for hot working; some may degrade or lose desirable properties when subjected to high temperatures

5. Recovery, Recrystallization and Grain Growth

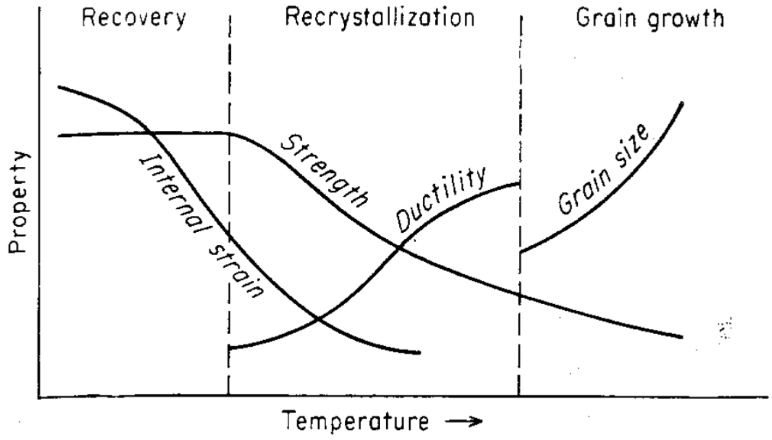


Figure 6-30 Schematic drawing indicating recovery, recrystallization, and grain growth and chief property changes in each region.

Recovery

Recovery refers to a specific process that occurs within a metal or alloy's microstructure when it's subjected to annealing (heating treatment). It's important to distinguish this from other metallurgical terms like "recrystallization" and "grain growth," which are also involved in annealing but happen at different stages and have different effects.

What happens:

- **Deformation:** When a metal is physically deformed (bent, stretched, etc.), its internal crystal structure gets messed up, introducing various defects like dislocations (lines of misaligned atoms). These defects increase the material's strength but decrease its ductility.
- **Recovery:** During annealing at **low temperatures**, these dislocations start "healing" themselves. They rearrange, climb, and even annihilate each other, reducing the overall density of defects. This process doesn't involve forming new grains.

Consequences:

- **Reduced Dislocation Density:** Due to the rearrangement and reduction of dislocations, the metal becomes softer and more ductile, meaning it can stretch more before breaking. However, its overall strength slightly decreases compared to the deformed state.
- **No New Grains:** Unlike recrystallization (which happens at higher temperatures), recovery doesn't involve forming new, strain-free

grains. The original grains remain, just with fewer internal defects.

Benefits:

- **Improved Ductility and Workability:** By reducing dislocation density, recovery makes the metal easier to shape and form further. This is useful for processes like wire drawing or deep drawing.

Key Points:

- Recovery occurs at **low annealing temperatures**.
- It involves **rearrangement and reduction of dislocations** within existing grains.
- It **improves ductility** but may slightly **reduce strength**.
- It **doesn't involve forming new grains**.

Recrystallization

Recrystallization is the process in which deformed grains of the crystal structure are replaced by a new set of stress-free grains that nucleate and grow until all the original grains have been consumed. The process is accomplished by heating the material to temperatures above that of crystallization. This process is utilized in the annealing of steel, to eliminate all the effects of strain hardening such as heavy plastic deformation produced during cold working.

When temperature is raised, the new, stress-free gains nucleate and grow inside the old deformed grains and also at the grain boundaries. This replaces the distorted grains produced by strain hardening. The metal’s mechanical properties revert back to their original, more ductile and weaker state.

The temperature above which the process occurs is not constant and is largely dependent on:

- Amount of time
- Steel composition
- Amount of cold work

The more strain hardening, the lower the recrystallization temperature and the smaller the new grain sizes. A minimum of between two and twenty percent cold work is required for recrystallization to occur.

Recrystallization temperature is typically one-third to one-half the melting point (in degrees Kelvin), and raises the atomic mobility, which results in recrystallization.

A minimum amount of deformation is essential to cause recrystallization. The amount of deformation should be such that sufficient number of lattice defects are developed in the crystal. These defects initiate the nucleation for the production of new grains.

The larger the degree of deformation, the lower is the recrystallization temperature. Recrystallization can be achieved at lower temperatures by increasing the holding time.

The recrystallization results in lower hardness and strength properties of the material, in addition to increased ductility. It might be an undesirable byproduct of another processing step.

Various applications include:

- Decreasing strength and hardness levels
- Increasing ductility
- Allowing recovery process by removal or reduction of cold-working effects
- Increasing equiaxed ferrite grains formed from elongated grains

This process is widely used in metal processing such as annealing of stamped parts in cold-rolled steel, and with forged parts to prepare them for subsequent operations like cold forming or machining.

Grain Growth

Grain growth refers to the **increase in the average size of individual grains** within a polycrystalline material (one with many small crystals).

- It typically occurs **after recrystallization has taken place**.
- Similar to recrystallization, it leads to a **reduction in the total grain boundary area** within the material.

Mechanisms of grain growth:

- The driving force for grain growth is the **reduction of total free energy**. Grain boundaries have higher energy compared to the crystal interiors, so reducing their area lowers the overall energy.
- There are two main mechanisms by which grain growth occurs:
    - **Normal grain growth:** Here, grain boundaries migrate due to **diffusion of atoms along the boundary**. Curved boundaries move towards their center of curvature, driven by the difference in surface energy across the curve. This leads to smaller grains shrinking and larger ones growing.

  - **Abnormal grain growth:** This is a less common and more rapid process, where a few **grains with specific orientations grow much larger** than the others, consuming their neighbors. This can be caused by the presence of specific impurities or by large differences in stored energy within the grains.

Factors affecting grain growth:

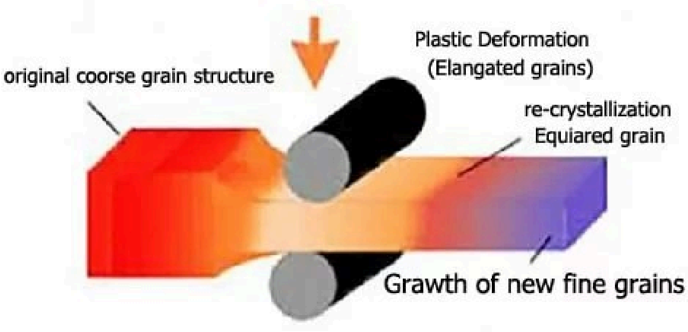
- **Temperature:** Grain growth rate increases significantly with temperature due to higher atomic mobility.
- **Time:** Longer annealing times allow for more extensive grain growth.
- **Material properties:** Different materials have different grain boundary energies and diffusivities, impacting growth rates.
- **Presence of impurities:** Some impurities can inhibit grain growth, while others can promote abnormal growth.
- **Grain size distribution:** The initial grain size distribution influences the subsequent growth behavior.

Impact of grain growth:

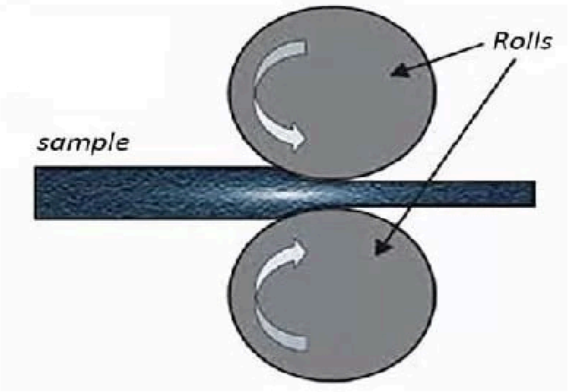
- Grain growth generally leads to a **softer and more ductile material** due to the decrease in grain boundaries, which act as barriers to dislocation movement.
- However, it can also **reduce strength** and other mechanical properties, especially when excessive.
- **Controlling grain size** through processing parameters is crucial for achieving desired properties in materials.

6. Rolling

The rolling process is a fundamental metalworking technique used to shape and reduce the thickness of metal materials by passing them through a pair of rotating rollers. This method is widely utilized in the manufacturing industry to produce various forms of metal, including sheets, plates, bars, and structural components.



Hot Rolling Process



Cold Rolling Process

Key Principles of Rolling

- **Compressive Stress**: The primary mechanism in rolling is the application of high compressive stress as the metal passes through the gap between two rotating rolls. This stress causes the material to deform plastically, reducing its thickness while increasing its length and width
- **Roll Gap Adjustment**: The gap between the rolls is critical; it must be smaller than the initial thickness of the material being processed. This ensures that the material is effectively compressed and deformed as it moves through the rollers. The roll gap can be adjusted throughout the process to accommodate varying thicknesses and achieve desired shapes
- **Frictional Forces**: Friction between the rolls and the material is essential for pulling the metal into the rolls. However, excessive deformation in a single pass can lead to slippage if the thickness reduction is too great, limiting the amount of deformation achievable at once
- **Multiple Passes**: To achieve significant reductions in thickness or complex shapes, materials often undergo multiple passes through the rollers. Each pass typically involves adjusting the roll gap closer to refine the shape and dimensions further[

Compare between Hot Rolling and Cold Rolling

Feature	Hot Rolling	Cold Rolling
Temperature	Above **recrystallization temperature** (typically **>1000°F or 540°C** for steel).	Below **recrystallization temperature** (room temperature or slightly higher).
Process	Metal is heated and passed through rollers to reduce thickness.	Metal is deformed at room temperature using high-pressure rollers.
Surface Finish	**Rough** surface with **oxide scale**.	**Smooth**, **shiny**, and precise surface finish.
Dimensional Accuracy	Less accurate due to shrinkage during cooling.	High precision in thickness and shape.
Strength & Hardness	Lower than cold-rolled metal.	Higher due to **strain hardening**.
Ductility	Higher (more formable).	Lower (work hardened, brittle).
Grain Structure	Coarse, equiaxed grains.	Fine, elongated grains due to plastic deformation.
Internal Stresses	Low residual stresses due to dynamic recrystallization.	High residual stresses, may require stress relief (annealing).
Production Cost	Lower (requires less energy and simpler equipment).	Higher (requires more energy and precision equipment).

Types of Roll pass

Two specific types of roll passes are the **open pass** and the **box pass**. Here's a detailed explanation of each:

Open Pass

- **Definition**: An open pass refers to a rolling process where the material is passed through rolls that have grooves designed to allow for significant deformation without completely enclosing the material. This type of pass is typically characterized by a simpler groove design.
- **Characteristics**:
  - The grooves in the rolls are often straight or slightly curved, allowing for easier flow of material.

  - Open passes are primarily used for initial reductions in thickness and are effective in forming basic shapes.
  - The design facilitates a larger reduction in cross-sectional area compared to more complex passes.
- **Applications**: Open passes are commonly used in the early stages of rolling processes, such as in breakdown passes, where the primary goal is to reduce the thickness of the metal significantly.

Box Pass

- **Definition**: A box pass involves grooves that are specifically designed to create a box-like shape during the rolling process. This type of pass is more complex than an open pass and is tailored to achieve specific cross-sectional profiles.
- **Characteristics**:
  - The grooves in box passes are shaped to form a rectangular or square cross-section, allowing for controlled shaping of the material.
  - Box passes can achieve substantial reductions in thickness, typically ranging from 10% to 30% per pass.
  - They often require tilting or rotating the workpiece between passes to ensure uniform deformation.
- **Applications**: Box passes are widely used in blooming mills and roughing mills, where precise control over the shape and dimensions of the final product is required. They are particularly effective for producing structural shapes like beams and bars.

Aspect	Open Pass	Box Pass
Groove Design	Simpler, allowing easier material flow	Complex, forming a box-like shape
Reduction Capability	Larger reductions in thickness	Controlled reductions (10% to 30%)
Applications	Early stages of rolling (breakdown)	Used in blooming and roughing mills
Material Shape	Basic shapes	Rectangular or square cross-sections

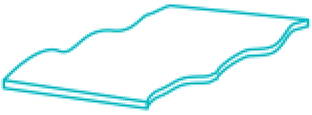
Defects:

There are mainly two forms of rolling defects:

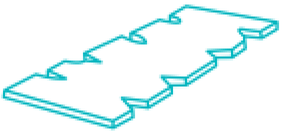
- Surface rolling defects.

- Internal structural rolling defects.

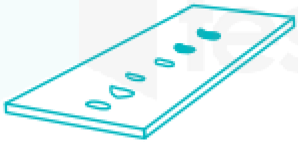
Surface defect



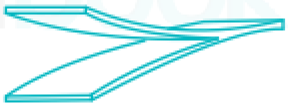
(a) Wavy Edges



(c) Edge Cracks



(b) Zipper Cracks in the center of the strip



(d) Alligatoring

Edge Cracks

Surface defects are visible imperfections on the metal's surface, often caused by external factors or material quality issues.

- **Impurities**: Includes dust, rust, or scratches on the metal surface, often resulting from mishandling or contamination during processing.
  - **Control**: Ensure proper handling and storage, and clean surfaces before rolling.
- **Edge Cracks**: Cracks that develop along the edges of the rolled material due to high tensile stresses.
  - **Control**: Adjust rolling parameters based on material strength and thickness; use edge rolls for uniformity.
- **Alligator Cracks**: Occur when the metal splits during rolling, resembling an alligator's mouth. This happens due to excessive pressure or uneven material composition.
  - **Control**: Use cambering techniques to reduce load and friction; select materials with uniform composition.
- **Wavy Edges**: Thinner edges compared to the center, resulting in a wavy appearance due to deflection under load.
  - **Control**: Implement hydraulic jacks to manage elasticity; use smaller diameter rolls to minimize deflection.
- **Zipper Cracks**: Small cracks that appear in the center of the workpiece due to bending under high pressure.
  - **Control**: Cambering can help alleviate tension; ensure proper roller alignment and pressure distribution.
- **Center Buckling**: Multiple humps along the center length of the workpiece caused by unequal roll pressures.

    - **Control**: Use crowned rollers to counteract deflection effects; ensure balanced pressure across the rollers.

Internal Structural Defects

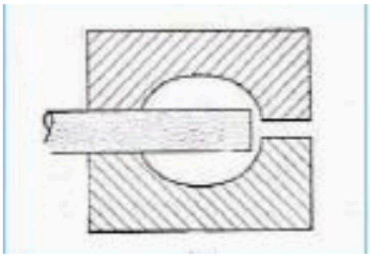
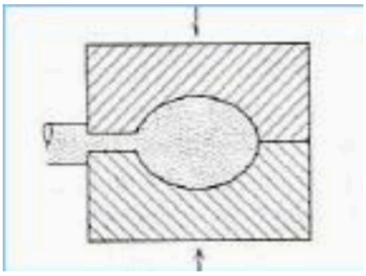
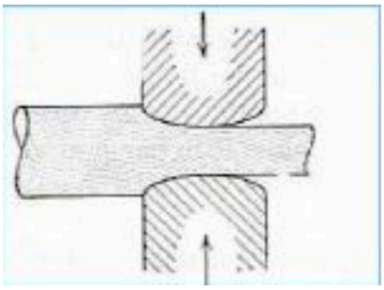
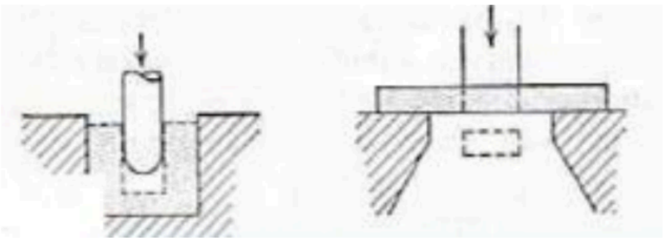
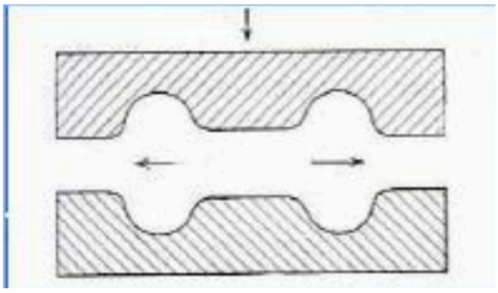
These defects are not visible on the surface but affect the material's internal structure and mechanical properties.

- **Laminations**: Layers within the metal that result from incomplete welding of inclusions during rolling.
    - **Control**: Discard defective ingots; select high-quality materials free from inclusions.
- **Flakes or Cooling Cracks**: Occur along edges due to decreased ductility during hot rolling.
    - **Control**: Monitor cooling rates and adjust processing parameters to maintain ductility.
- **Barreling**: A defect where the rolled product becomes wider at its center than at its edges due to roll bending.
    - **Control**: Use cambered rolls to maintain uniform thickness and prevent barreling

7. Forging

This is the working of metal into a useful shape by hammering or pressing.

- The oldest of the metalworking arts (primitive blacksmith).
- Replacement of machinery occurred during early the Industrial revolution.
- Forging machines are now capable of making parts ranging in size of a bolt to a turbine rotor.
- Most forging operations are carried out hot, although certain metals may be cold-forged.

The two broad categories of forging processes are

- **Open-die forging**
  - Open-die forging is carried out between fiat dies or dies of very simple shape. The process is used mostly for large objects or when the number of parts produced is small.
- **Closed-die forging**
  - In closed-die forging the workpiece is deformed between two die halves which carry the impressions of the desired final shape. The workpiece is deformed under high pressure in a closed cavity, and thus precision forgings with close dimensional tolerances can be produced.

Edging is used to shape the ends of the bars and to gather metal. The metal flow is confined in the horizontal direction but it is free to flow laterally to fill the die.

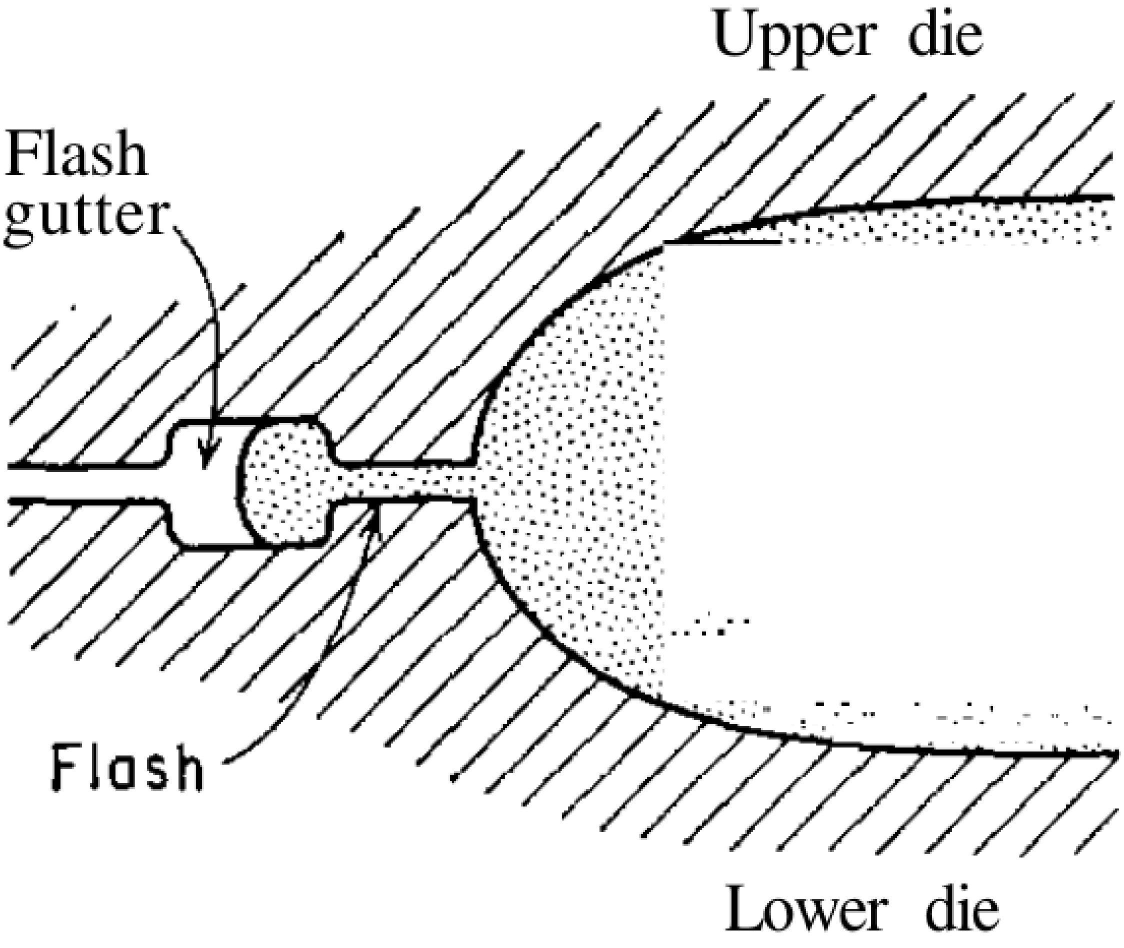
Drawing is used to reduce the cross-sectional area of the workpiece with concurrent increase in length.

Piercing and punching are used to produce holes in metals.

Fullering is used to reduce the cross-sectional area of a portion of the stock. The metal flow is outward and away from the centre of the fuller. i.e.,forging of connecting rod for an internal-combustion engine.

Swaging is used to produce a bar with a smaller diameter (using concave dies).

It is important to use enough metal in the forging billet so that the die cavity is completely filled. Because it is difficult to put just the right amount of metal in the correct places during fullering and edging, it is customary to use a slight excess of metal. When the dies come together for the finishing step, the excess metal squirts out of the cavity as a thin ribbon of metal called flash. In order to prevent the formation of a very wide flash, a ridge, known as a flash gutter, is usually provided. The final step in making a closed-die forging is the
removal of the flash with a trimming die.



Properties of Forged Products

Forging is a **metal shaping process** where a material is **plastically deformed** using **compressive forces** to achieve the desired shape. Forged products exhibit superior **mechanical, thermal, and structural properties**, making them ideal for high-performance applications.

Mechanical Properties

- **High Strength** – Due to refined grain structure and strain hardening during forging.
- **High Toughness** – Can absorb impact loads without fracturing.
- **Good Fatigue Resistance** – Withstands repeated stress cycles, making it suitable for structural and automotive components.
- **Improved Hardness** – Especially in cold-forged parts due to work hardening.
- **Excellent Wear Resistance** – Can sustain high loads and friction-based applications.

Structural Properties

- **Fine & Uniform Grain Structure** – Due to dynamic recrystallization during forging, enhancing strength and durability.
- **Directional Grain Flow** – Aligns along the shape of the product, improving load-bearing capacity.
- **Reduced Porosity & Internal Defects** – Unlike cast products, forging eliminates voids and inclusions.

Thermal & Corrosion Properties

- **Better Heat Resistance** – Forged components can withstand high temperatures without failure.
- **Improved Corrosion Resistance** – Compared to cast or welded components, forged parts have fewer impurities, reducing corrosion susceptibility.

Dimensional Accuracy & Surface Properties

- **Better Dimensional Stability** – Less distortion during machining and in service.
- **Good Surface Finish** – Especially in precision-forged components, reducing the need for post-processing.

Comparison with Other Manufacturing Methods

Property	Forged Products	Cast Products	Machined Products
Strength	High	Moderate	Moderate
Toughness	Excellent	Low	Moderate
Porosity	Negligible	High	None
Grain Structure	Oriented & Fine	Random	Random
Wear Resistance	High	Moderate	High

Defects

Surface Defects

- **Hairline Cracks (Splitting)**: Fine cracks on the surface caused by elongated subcutaneous bubbles in the steel during rolling.
  - **Control**: Ensure thorough inspection of raw materials and remove defective ingots before forging.
- **Scab**: A thin, easily peelable layer on the surface that results from splashing during casting.
  - **Control**: Proper cleaning of the surface before forging to remove scabs.
- **Folds (Folding)**: Folds appear at the ends of the forged part due to incorrect roll groove sizing or burrs.
  - **Control**: Regular maintenance of rolling equipment and proper sizing to prevent burr formation.
- **Non-metallic Inclusions**: Elongated or broken inclusions within the material, often due to chemical reactions during melting.
  - **Control**: Use high-purity materials and refine melting processes to minimize inclusions.

Internal Structural Defects

- **Laminated Fracture**: Layered fractures in the material, often caused by non-metallic inclusions or dendritic segregation.
  - **Control**: Optimize raw material selection and monitor processing conditions to reduce inclusions.
- **Segregation Zones**: Variations in alloy composition leading to inconsistent material properties.
  - **Control**: Ensure homogenous mixing of alloying elements during production.
- **White Spots**: Internal cracks caused by high hydrogen content and rapid cooling.

    - **Control**: Control hydrogen levels during melting and avoid rapid cooling after forging.

Dimensional Defects

- **Unfilled Sections**: Areas of the forging that are not completely filled, leading to weak spots.
    - **Control**: Optimize die design and ensure proper metal flow into the die cavity.
- **Cold Shut**: Occurs when two streams of metal do not fuse properly, leaving a weak joint.
    - **Control**: Maintain appropriate temperatures and ensure proper die filling techniques.

Warping and Distortion

- **Warping**: Deformation after cooling due to residual stresses or uneven cooling.
    - **Control**: Implement controlled cooling methods and stress-relieving treatments post-forging.

Improper Die Fill

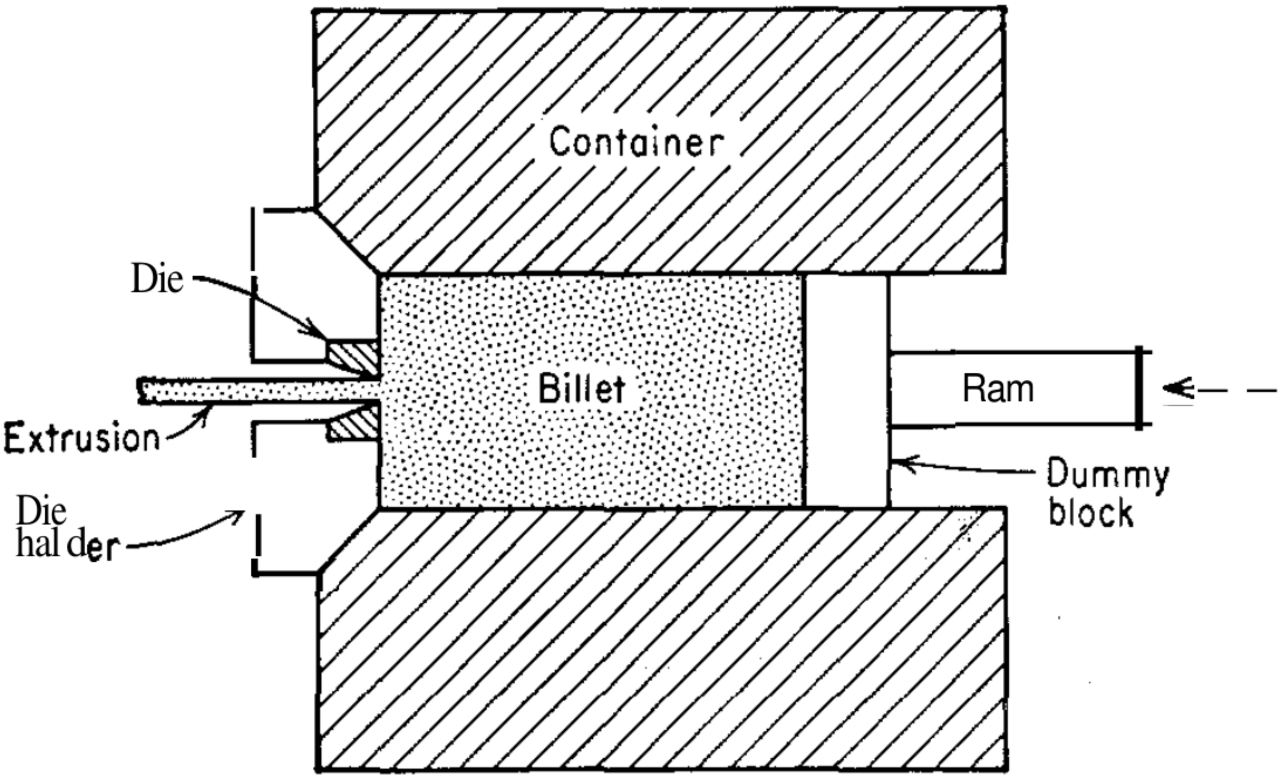
- **Improper Die Fill**: When the metal does not completely fill the die cavity, resulting in incomplete parts.
    - **Control**: Ensure proper metal temperatures and optimize die designs for better flow characteristics.

8. Extrusion

Extrusion is the process by which a block of metal is reduced in cross section by forcing it to flow through a die orifice under high pressure. In general, extrusion is used to produce cylindrical bars or hollow tubes, but shapes of irregular cross section may be produced from the more readily extrudable metals, like aluminum.
Because of the large forces required in extrusion, most metals are extruded hot under conditions where the deformation resistance of the metal is low. However, cold extrusion is possible for many metals and has become an important commercial process.

The two basic types of extrusion are **direct extrusion** and **indirect extrusion**.

Direct Extrusion

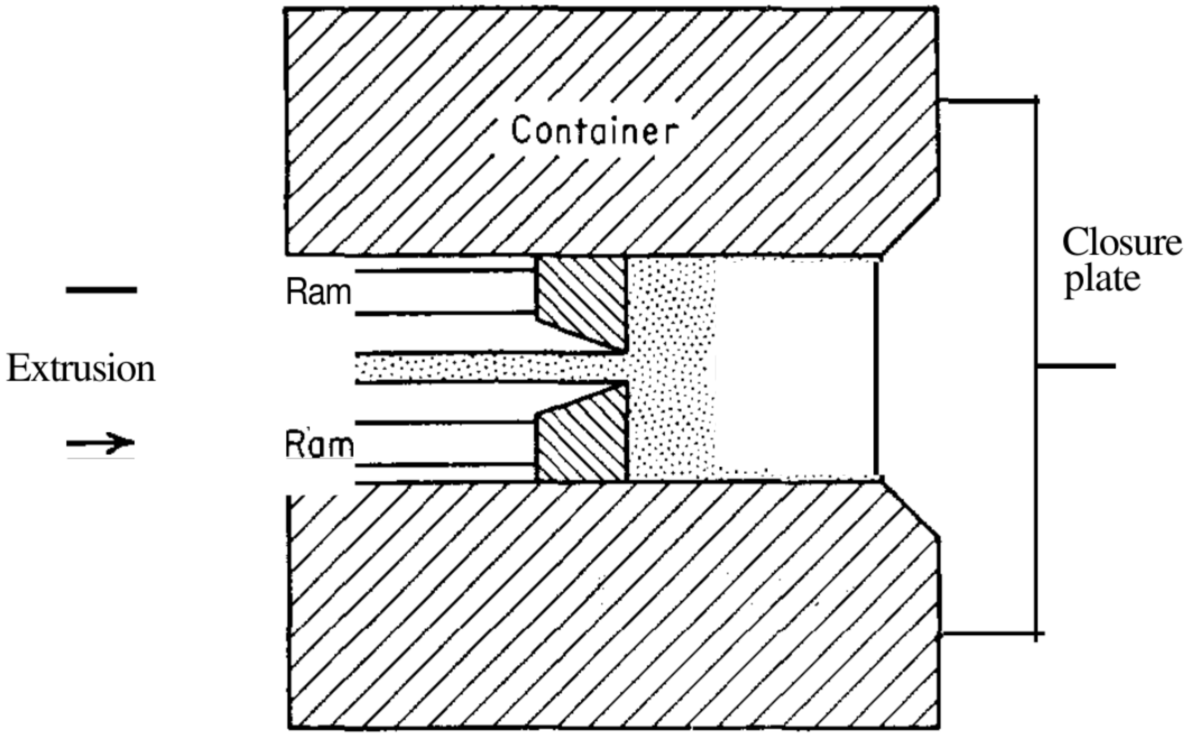


Direct extrusion

- **Definition**: Also known as forward extrusion, direct extrusion involves pushing a heated billet through a die using a ram. The material flows in the same direction as the ram's motion.
- **Process**:

  - The billet is placed in a container, and a ram forces it through the die.
  - A dummy block is often used to separate the billet from the ram.
  - As the ram moves forward, the material is extruded out of the die, creating a continuous profile.
- **Advantages**:
  - Simplicity of setup and operation.
  - Versatile for producing various shapes and sizes.
- **Disadvantages**:
  - Higher force requirements due to friction between the billet and the container walls, especially at the start and end of the process.
  - Increased risk of defects such as cracks due to heat generated from friction.
  - Not all of the billet is utilized; some material remains as a butt end that cannot be extruded.

Indirect Extrusion



Indirect extrusion

- **Definition**: Also referred to as backward extrusion, indirect extrusion involves moving both the container and the billet together while keeping the die stationary. The material flows in the opposite direction to that of the ram's motion.

- **Process**:
  - The die is attached to a stem that remains fixed while the ram pushes both the billet and container forward.
  - This design minimizes friction since the billet does not slide against the container walls.
- **Advantages**:
  - Lower force requirements due to reduced friction, allowing for larger billets and enhanced speed.
  - Less heat generation from friction reduces the risk of cracking during extrusion.
  - More uniform flow results in fewer defects and better mechanical properties in the extruded product.
- **Disadvantages**:
  - Limited versatility compared to direct extrusion; cross-sectional shapes are constrained by the size of the stem.
  - Surface defects on the billet can affect product quality, necessitating pre-treatment like cleaning or machining.

Comparison

Aspect	Direct Extrusion	Indirect Extrusion
Direction of Flow	Same as ram motion	Opposite to ram motion
Friction	Higher friction leads to greater force	Lower friction reduces force requirements
Heat Generation	More heat due to friction	Less heat generation
Defect Risk	Higher risk of cracks and defects	Lower risk of defects
Material Utilization	Some material wasted (butt end)	More efficient use of material
Versatility	More versatile for various shapes	Limited by stem size

Defects In Extruded Products

Owing to the considerable deformation associated with extrusion operations, a number of defects can occur in extruded products. The defects can be classified into the following categories

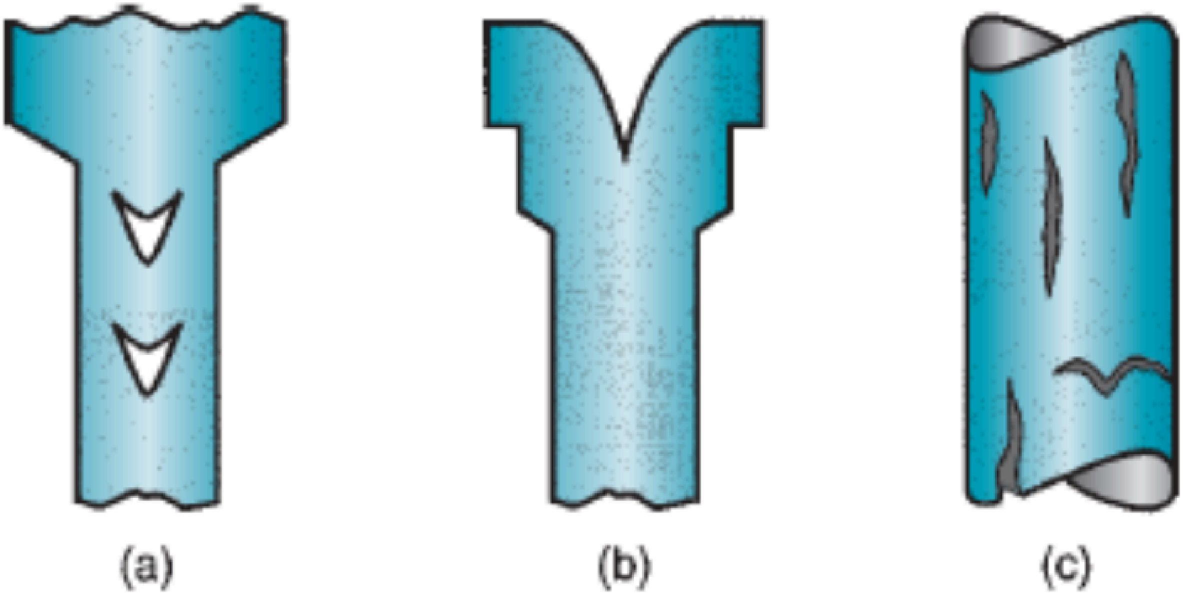


Fig (6.7) Some common defects in extrusion: (a) centerburst, (b) piping, and (c) surface cracking.

- **Centerburst**
  - This defect is an internal crack that develops as a result of tensile stresses along the centerline of the work part during extrusion. Although tensile stresses may seem unlikely in a compression process such as extrusion, they tend to occur under conditions that cause large deformation in the regions of the work away from the central axis. The significant material movement in these outer regions stretches the material along the center of the work. If stresses are great enough, bursting occurs. Conditions that promote centerburst are high die angles, low extrusion ratios, and impurities in the work metal that serve as starting points for crack defects. The difficult aspect of centerburst is its detection. It is an internal defect that is usually not noticeable by visual observation. Other names sometimes used for this defect include arrowhead fracture, center cracking, and chevron cracking.
- **Piping**
  - Piping is a defect associated with direct extrusion. As in Figure 6.7(b), it is the formation of a sink hole in the end of the billet. The use of a dummy block whose diameter is slightly less than that of the billet helps to avoid piping. Other names given to this defect include tailpipe and fishtailing.
- **Surface cracking**

    - This defect results from high workpart temperatures that cause cracks to develop at the surface. They often occur when extrusion speed is too high, leading to high strain rates and associated heat generation. Other factors contributing to surface cracking are high friction and surface chilling of high temperature billets in hot extrusion.

The manufacturing of seamless pipes

The manufacturing of seamless pipes through extrusion is a specialized process that involves several key stages. This method is particularly effective for producing high-strength alloy steel tubes and offers advantages in terms of material efficiency and product quality.

Step-by-Step Manufacturing Process

- **Raw Material Preparation**:
    - High-quality steel billets are selected as raw materials.
    - The billets are heated to approximately 1200 degrees Celsius in a furnace, using fuels like hydrogen or acetylene to ensure proper melting and ductility
- **Billet Inspection**:
    - After heating, the billets undergo inspections for appearance, dimensions, and chemical composition to ensure they meet production standards
- **Perforation**:
    - The heated billet is fed into a punching machine that creates a central hole, transforming it into a hollow tube shape. This step is crucial as it sets up the material for the subsequent extrusion phase
- **Extrusion**:
    - The perforated billet is then placed into an extruder where it is forced through a die. This action gradually deforms the billet into a seamless pipe shape. The die's design determines the final dimensions of the pipe
- **Cooling**:
    - After extrusion, the newly formed pipe is cooled using water or air to stabilize its structure and prevent warping
- **Sizing and Straightening**:

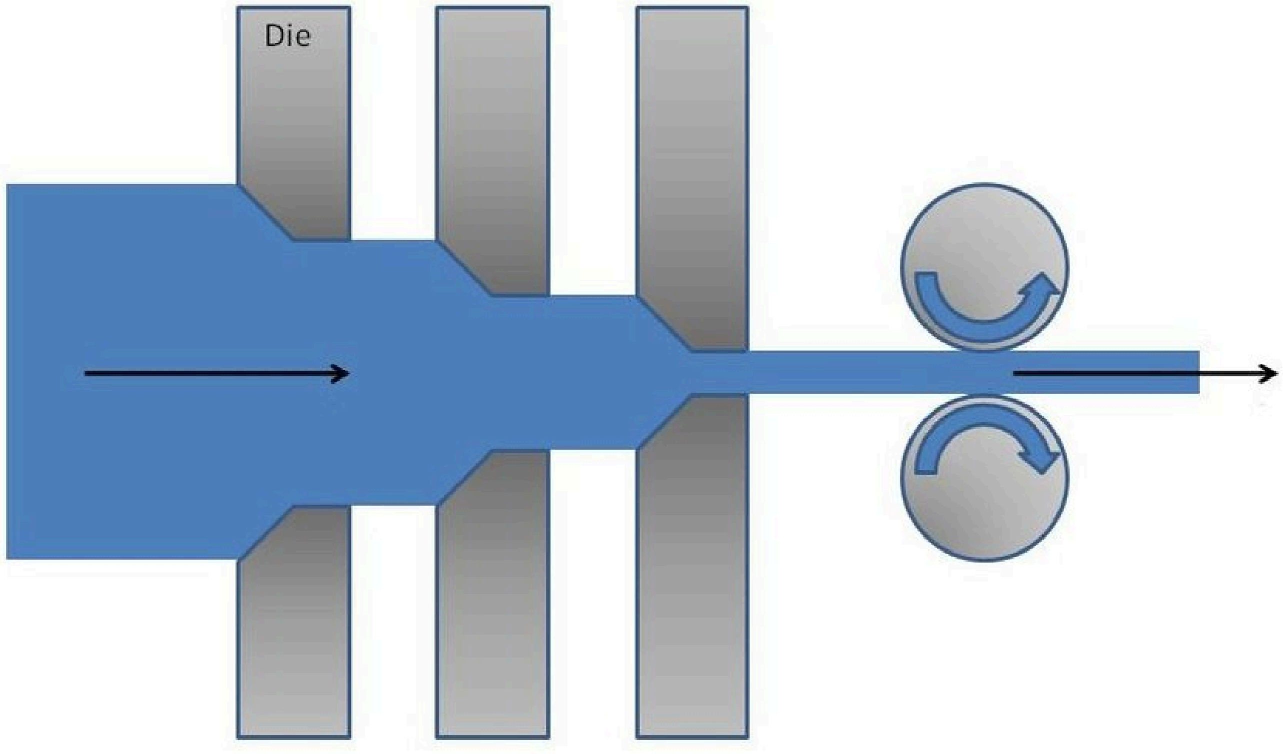
- The pipe may undergo sizing processes to ensure precise diameter and wall thickness. It is then straightened to achieve uniformity

9. Wire drawing

Wire drawing is a metalworking process used to reduce the cross-section of a wire by pulling it through one or more dies. This method is widely employed in the production of various wire products, including electrical wiring, cables, and springs.

Elementary Principle of Wire Drawing

The fundamental principle of wire drawing involves applying tensile force to a wire, which is then drawn through a die with a smaller diameter than the original wire. As the wire passes through the die, its cross-sectional area decreases while its length increases, adhering to the principle of volume conservation.



Key Steps in the Wire Drawing Process

- **Preparation**:
  - The wire is prepared by reducing its initial end diameter through processes like hammering or rolling, allowing it to fit through the die.
- **Drawing**:
  - The prepared wire is pulled through a series of progressively smaller dies. Each die reduces the diameter further, typically

requiring multiple passes to achieve the desired final size.

- **Cold Working**
  - Wire drawing is primarily a cold working process, meaning it is performed at room temperature. This process enhances the mechanical properties of the wire, such as strength and hardness, due to strain hardening.
- **Lubrication**:
  - Lubricants are applied during drawing to minimize friction between the wire and the die, improving surface finish and prolonging die life. Various lubrication methods include wet drawing (immersion in lubricant) and dry drawing (coating with lubricant).
- **Annealing**:
  - Intermediate annealing may be necessary after significant reductions in area (greater than 50%) to relieve stresses and restore ductility before further drawing.

Wire drawing is a critical manufacturing process that can lead to various defects, which can be classified into two main categories: **surface defects** and **internal defects**. Understanding these defects is essential for improving product quality and ensuring the reliability of drawn wires.

Wire Drawing Defects

Surface Defects

Surface defects are imperfections found on the outer layer of the wire, often resulting from issues during the drawing process or from the condition of the dies used. Common surface defects include:

- **Seams**: Longitudinal scratches or folds that can occur during the drawing process. These seams may open up during subsequent operations, leading to quality control issues
- **Scratches and Die Marks**: These can result from poor lubrication, inadequate die maintenance, or improper selection of process parameters. Such marks can affect both aesthetics and performance
- **Slivers**: Thin strips or flakes of material that detach from the wire surface during drawing. They can be caused by defects in the raw material or improper processing conditions[
- **Laminations**: These appear as layers or splits in the material, often due to non-metallic inclusions or inadequate melting practices prior to drawing
- **Embedded Scale**: This defect occurs when scale (oxidized metal) becomes trapped in the wire surface during heating processes

Internal Defects

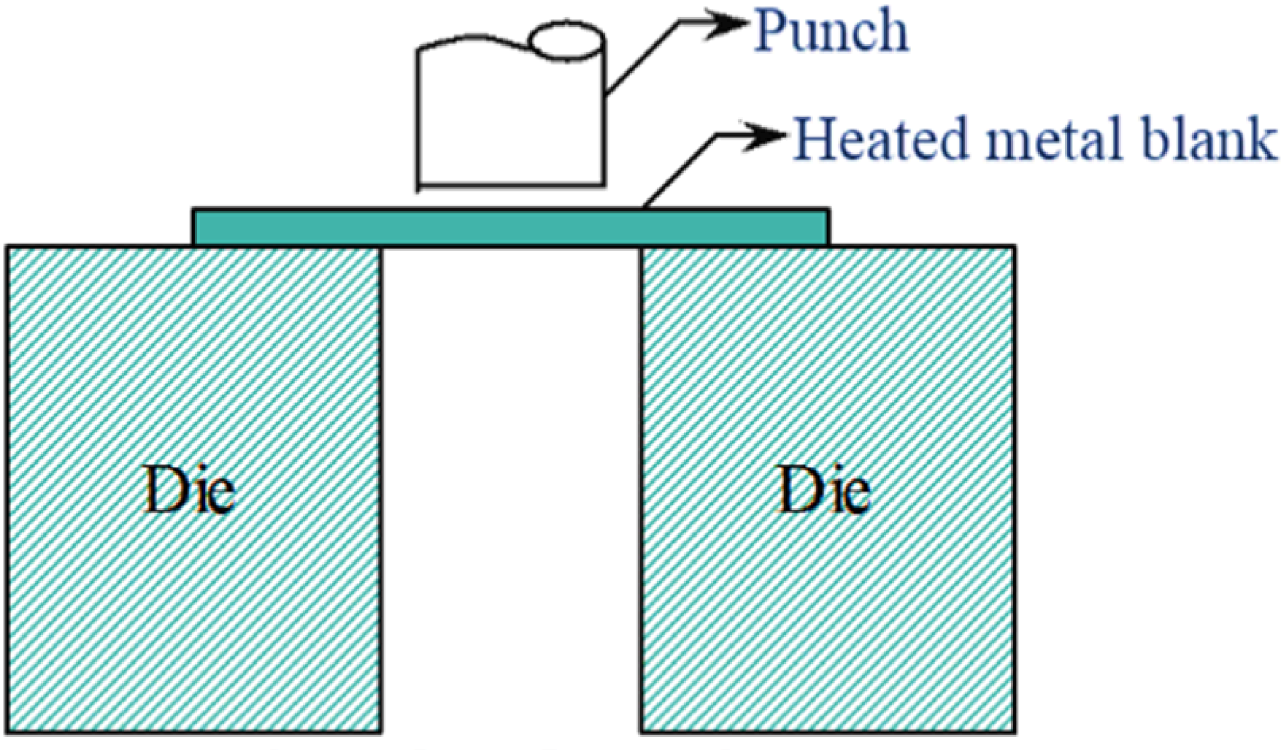
Internal defects are flaws that occur within the wire and may not be visible from the surface. They can significantly impact the mechanical properties and performance of the wire. Key internal defects include:

- **Center Cracking (Chevron Cracking)**: This defect arises due to tensile hydrostatic stress in the centerline of the wire, often occurring with low die angles and insufficient reductions during drawing
- **Residual Stresses**: Cold-drawn products often exhibit residual stresses due to non-uniform deformation. These stresses can lead to warping or stress-corrosion cracking over time if not properly managed
- **Cracks**: Internal cracks can develop due to excessive tensile forces during drawing, often exacerbated by poor material quality or processing conditions

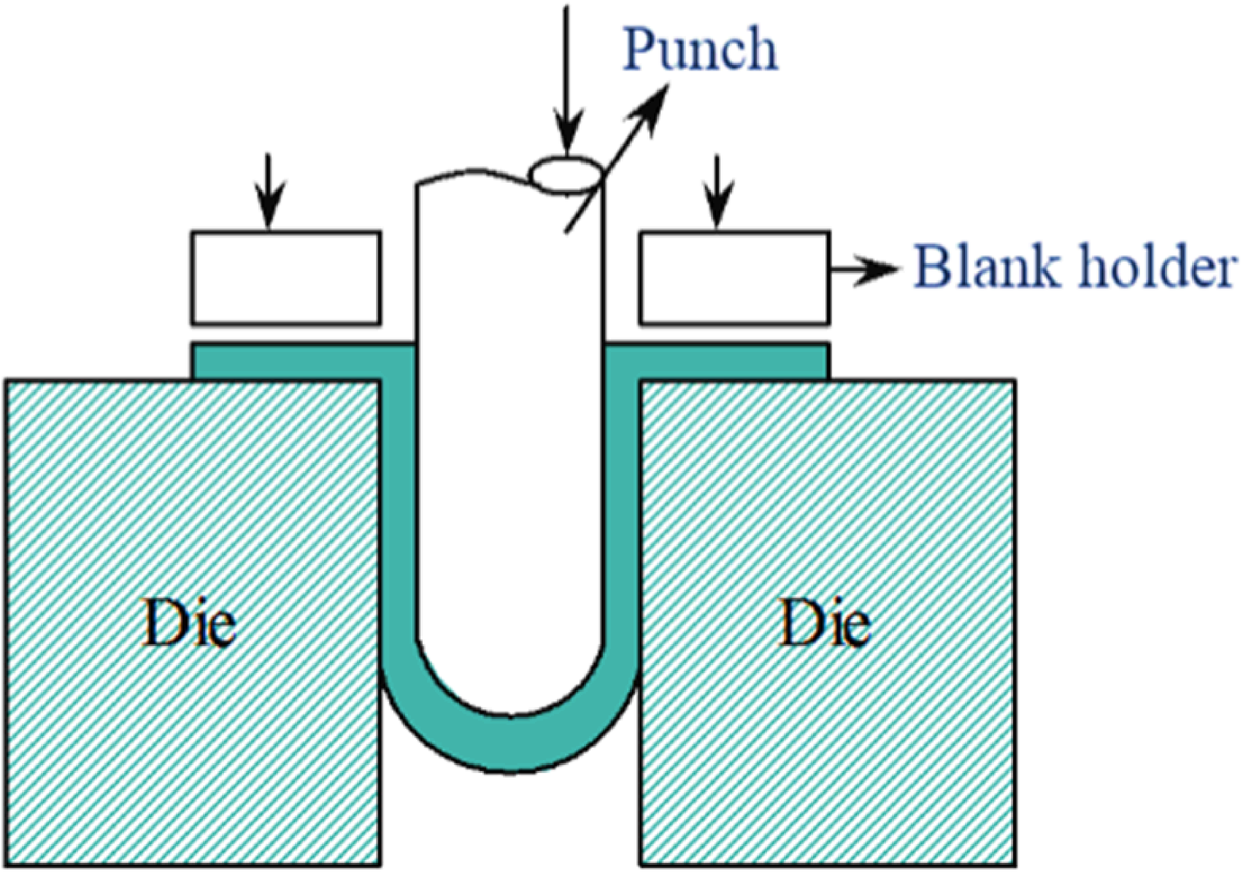
10. Forming methods

Deep drawing

Deep drawing is a specialized metal forming process used to create complex shapes from flat sheets of metal. This technique is particularly effective for producing parts that are deep relative to their diameter, such as cups, containers, and automotive components.



(i) Before Operation



(ii) After Operation

Process Overview

The deep drawing process involves the following key steps:

- **Blank Preparation**:
  - A flat sheet of metal, known as a blank, is cut to the required dimensions. The thickness of this sheet remains constant throughout the process.
- **Positioning**:
  - The blank is placed over a die cavity. A blank holder may be used to keep the blank in place and control material flow.
- **Drawing**:
  - A punch descends and forces the central part of the blank into the die cavity. As the punch moves downwards, it draws the metal into the die, creating a three-dimensional shape.
- **Material Flow**:
  - The metal is drawn radially into the die, which allows it to maintain its thickness while achieving significant depth. The process relies on material retention, meaning that the original sheet thickness is preserved.
- **Finishing**:
  - After the initial draw, additional operations may be performed to refine the shape or add features. Complex shapes may require multiple drawing stages.

Applications

Deep drawing is widely used in various industries for manufacturing items such as

- Cans and containers
- Automotive body panels
- Kitchen sinks
- Aerospace components

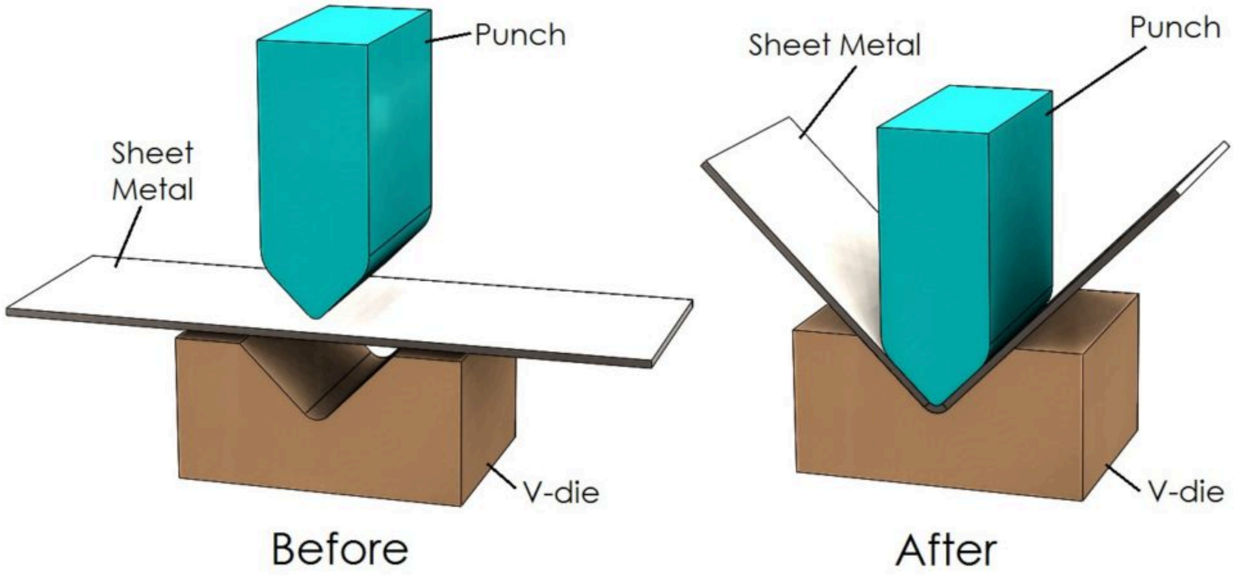
Advantages

- High production efficiency with minimal waste.
- Consistent quality and uniformity across large production runs.
- Capability to produce complex shapes that would be difficult or impossible to achieve through other forming methods.

Sheet metal forming encompasses various techniques used to reshape flat sheets of metal into desired geometries without removing material. Three primary processes within this domain are **bending**, **shearing**, and **blanking**.

Each technique serves distinct purposes in manufacturing and has unique characteristics.

Bending



Bending is a process that involves deforming a sheet metal along a straight axis to create an angle or curve. This operation is performed without cutting the material, thus preserving its volume and thickness.

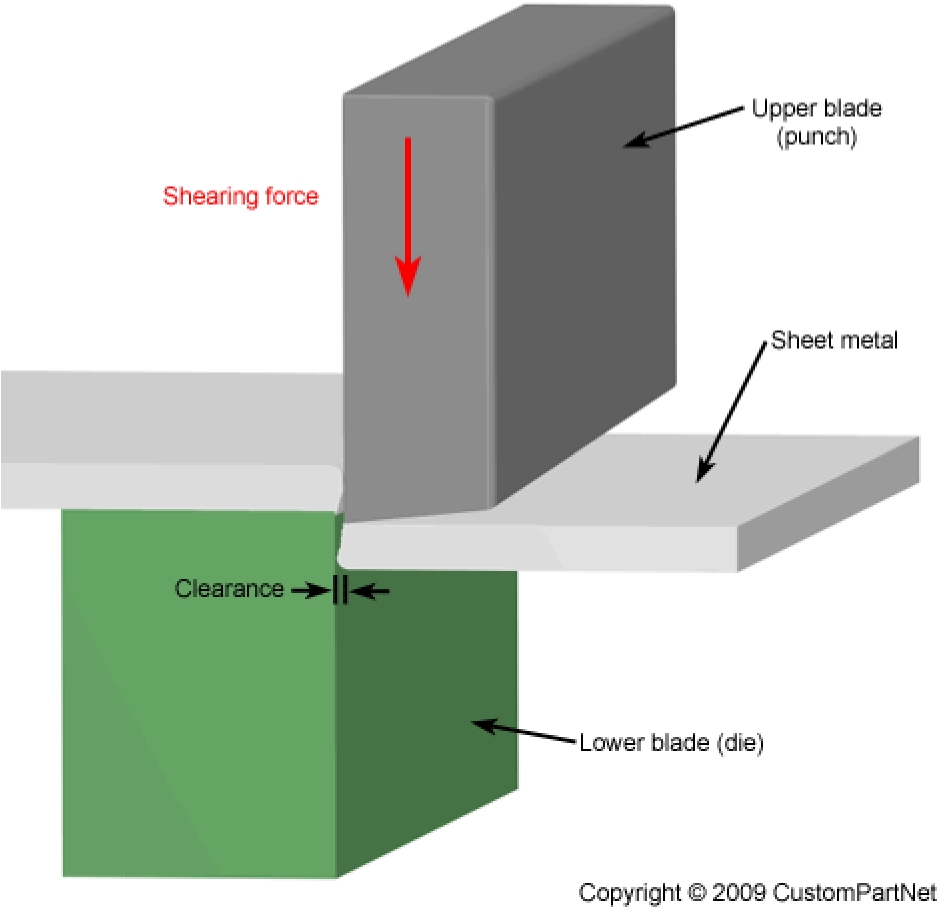
Key Characteristics

- **Equipment**: Typically executed using a press brake, which consists of a punch (upper tool) and a die (lower tool).
- **Techniques**:
  - **V-Bending**: The most common method where the sheet is bent into a V-shaped die.
  - **Air Bending**: Allows for flexibility in achieving various angles with partial contact between the die and workpiece.
  - **Coining**: Involves high force to create precise bends with minimal springback.
  - **Roll Bending**: Used for forming cylindrical shapes through a series of rollers.

Applications:

Bending is widely used in the fabrication of brackets, enclosures, automotive parts, and architectural features.

Shearing



Shearing is a cutting process used to remove sections from a sheet metal by applying a shearing force. This technique is essential for producing straight cuts in sheets, strips, or coils.

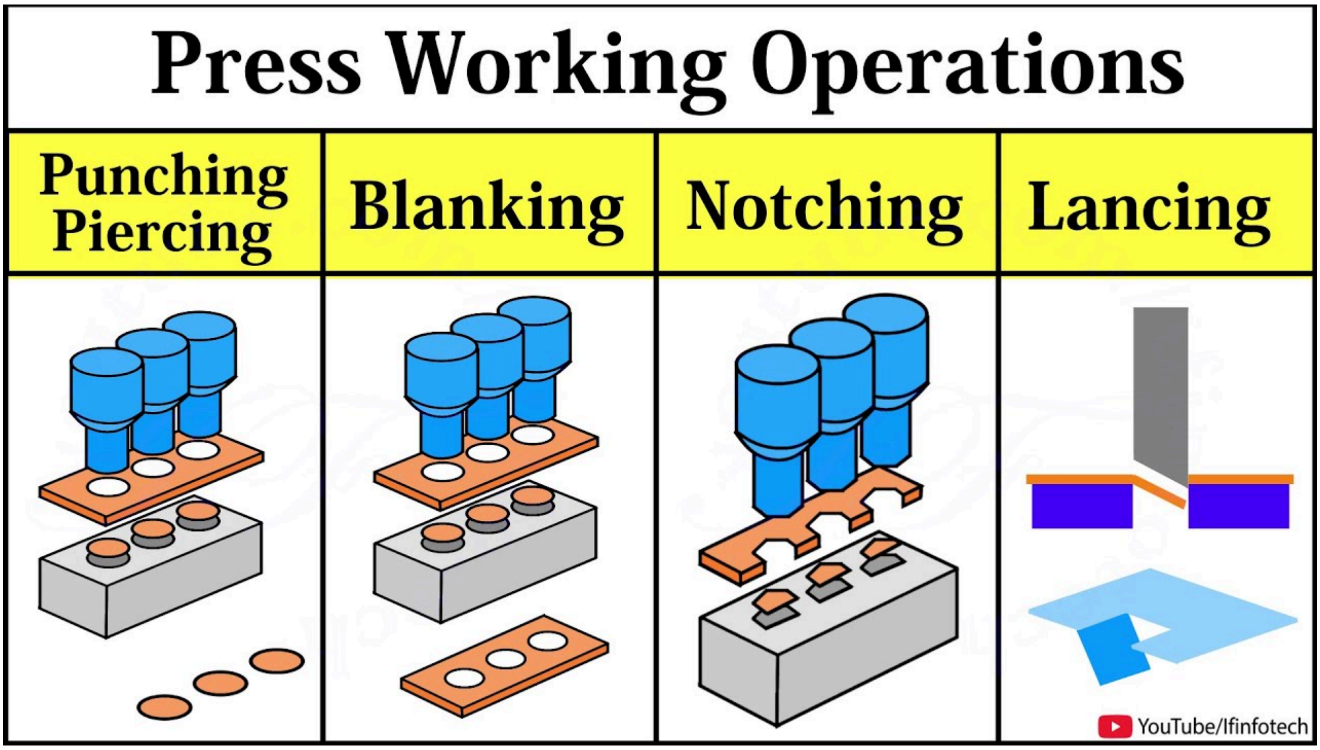
Key Characteristics

- **Process**: Involves two cutting edges (the upper blade and lower blade) that slide past each other to shear the material.
- **Types of Shearing**:
    - **Straight Shearing**: Produces straight cuts along the length of the sheet.
    - **Notching**: Removes small sections from the edges or corners of the sheet.

Applications

Shearing is commonly employed for preparing blanks for further processing, trimming excess material, and creating specific shapes from larger sheets.

Blanking



Blanking is a specific type of shearing process where a punch cuts out a flat piece (blank) from a larger sheet of metal. The blank can then be used as a workpiece for further operations.

Key Characteristics

- **Process**: The punch presses down into the sheet metal, cutting out the desired shape while leaving behind scrap material.
- **Difference from Shearing**: While shearing typically refers to cutting without forming a specific shape, blanking focuses on creating usable parts from the sheet.

Applications

Blanking is widely used in manufacturing components such as washers, brackets, and other parts that require precise shapes for assembly or further processing.